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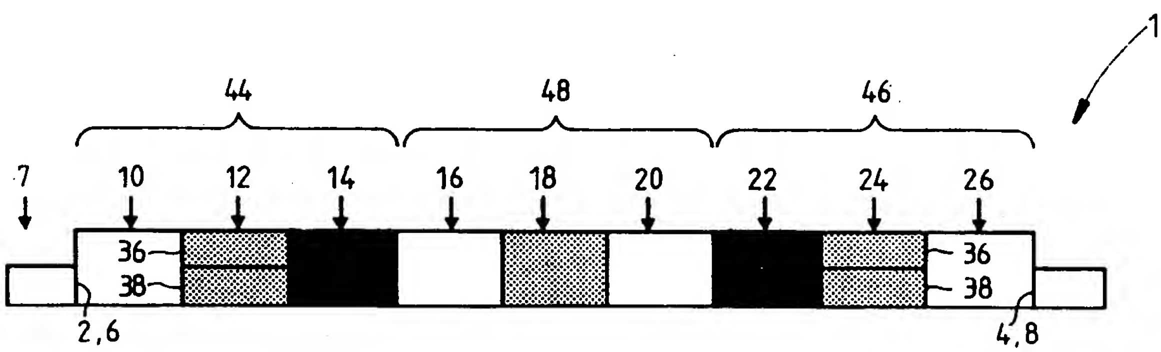


(57) Abstract

An optical circulator including at least four ports, polariser means (10, 16, 20, 26) reciprocal rotator means, and Faraday rotators (14, 22), the circulator being substantially tolerant to errors induced by the Faraday rotators and adapted to operate as a four port circulator. An optical circulator having at least three ports and consisting of polariser means (10, 16, 20, 26) and Faraday rotators (14, 22), the circulator being adapted to operate as a three port circulator.

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# AN OPTICAL CIRCULATOR

The present invention relates to an optical circulator.

Optical circulators are used in optical telecommunications systems primarily as a junction device to redirect light from one optical fibre to another. A four port circulator operates to output light received on the first port to the second port, light received on the second port is directed to the third port, light incident on the third port is output on the fourth port, and light received on the fourth port is output on the first port. A three port circulator operates to output light incident on the first port to the second port, and light received on the second port is output on the third port.

Optical circulator configurations, such as that disclosed in "High-isolation polarisation-independent optical circulator coupled with single-mode fibers", Yohji Fujii, Journal of Lightwave Technology, Vol. 9, No. 4, April 1991, pages 456 to 460, are generally bulky and also tend to employ beam splitters which can give rise to lower isolation between ports.

European Patent Publication No. 491 607 (Application No. 91403393.1) discloses a number of optical circulator configurations which allow the beam splitters to be replaced by birefringent crystals, which are used to form components known as spatial walk-off polarisers (SWPs). An SWP formed from a birefringent crystal, such as calcite, is able to separate incident light into two orthogonal polarisation components by affecting the direction of travel of the components through the crystal so as to "walk" one of the polarisation components away from the other. The crystal is cut in a predetermined manner to give the desired walk-off and polarisation effects. The configurations described in the European publication also include Faraday rotators which are able to rotate polarised signals of a wavelength band $\lambda$ by a selected number f degrees in a set

clockwise r anticlockwise direction, regardless f whether the signals travel through the rotator in a forward or reverse direction. Faraday rotators are normally constructed from YIG, which is Yttrium based, or BIG, which is Bismuth substituted YIG. The Faraday material of the rotator is surrounded by a magnet which generates a magnetic field and dictates the rotation direction imparted by the rotator on incident polarised light. The Faraday material has a characteristic Verdet constant which indicates the degree of rotation which will be imparted by a certain length of the material on an incident signal when a given magnetic field is applied to the material. The Verdet constant may be positive or negative, denoting the direction of rotation. The magnetic field generated by the surrounding magnet is such that the material is driven into saturation so that the optical rotation is relatively uniform across the aperture or cross–section presented by the rotator to incident light. The desired rotation to be performed by the rotator is obtained by adjusting the length of Faraday material through which the incident light must pass.

Faraday rotators are known to introduce errors in circulator assemblies by emitting polarised components which have not been rotated precisely as intended. Therefore it is advantageous to provide circulator configurations which take these induced errors into account, and are therefore error tolerant, in that the erroneous polarisation components produced by the rotators are inhibited from appearing at any of the input or output ports of a circulator.

The European publication discloses a circulator, with reference to Figure 11, which includes four ports and is error tolerant but it is unable to operate as a four port circulator in that light incident on the fourth port is not output on the first port. Also the configuration requires two Faraday rotators which are divided into four Faraday material segments. The segments of Faraday material are used to rotate polarised signals in different directions within the one rotator. This can be achieved by placing respective magnets around each segment so as to impart magnetic fields of different directions on the segments. However, this is disadvantageous as the provision of respective magnets around each segment significantly increases the size of the circulator assembly. The only other alternative is to use segments of Faraday material which have different Verdet constants, however, this has proved impractical or impossible to implement as the

segments would normally have different lengths to achieve the same magnitude of rotation but in an opposite direction. A practical implementation of a Faraday rotator for a circulator assembly requires segments which are all of similar length and exhibit a similar refractive index with respect to incident light. Ideally the Faraday segments would have the same length and refractive index for the incident light.

The European publication further discloses, with reference to Figure 4, a three port circulator which is able to perform a three port circulator function and is error tolerant. The circulator includes spatial walk-off polarisers, Faraday rotators and half-wave plates. Half-wave plates can be cut from quartz and are used as optical rotators to rotate optical polarised signals of a wavelength λ by a predetermined number of degrees. Unlike Faraday rotators, the half-wave plates will rotate a polarised signal in one direction as it passes therethrough in a forward direction but will perform a reciprocal rotation, by rotating the signal in the opposite direction, when it passes through the wave plate in the reverse direction.

It is advantageous to provide a circulator configuration which does not require any half-wave plates. This reduces the numbers of components in the circulator, thereby reducing the complexity and cost of the circulator. It also enables a broader wavelength device to be produced as the wavelength dependency of the half-wave plates is no longer a factor in the design. Alignment problems between components are also reduced as it is no longer necessary to take into account half-wave plate sections included in an in-line circulator assembly.

According to a first aspect of the present invention there is provided an optical circulator including at least four ports, polariser means, reciprocal rotator means, and Faraday rotators, said circulator being substantially tolerant to errors induced by said Faraday rotators and adapted to operate as a four port circulator.

According to a second aspect of the present invention there is provided an optical circulator having at least three ports and consisting of polariser means and Faraday rotators, said circulator being adapted to operate as a three port circulator.

Preferred embodiments of the present invention are her inafter described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 is a side view of the parts of a first preferred embodiment of a four port optical circulator;

Figure 2 is a cross-sectional view of a first half-wave plate arrangement of the circulator of Figure 1;

Figure 3 is a cross-sectional view of a third half-wave plate arrangement of the circulator of Figure 1;

Figure 4 is a plan view of the parts of the circulator of Figure 1;

Figure 5 is polarisation diagrams for the circulator of Figure 1;

Figure 6 is polarisation diagrams for the circulator of Figure 1 when rotators of the circulator introduce errors;

Figure 7 is a side view of the parts of a second preferred embodiment of a four port optical circulator;

Figure 8 is a diagram of the functions performed by the SWPs and half-wave plate arrangements of the circulator of Figure 7;

Figure 9 is a plan view of the circulator of Figure 7;

Figure 10 is polarisation diagrams for the circulator of Figure 7;

Figure 11 is polarisation diagrams for the circulator of Figure 7 when the first rotator of the circulator introduces errors;

Figure 12 is polarisation diagrams for the circulator of Figure 7 when the second rotator of the circulator introduces errors;

Figure 13 is a perspective view of a laboratory configuration of a circulator of Figure 1;

Figures 14 to 16 are images obtained by an infrared camera of the configuration of Figure 13;

Figure 17 is a side view of a third preferred embodiment of an optical circulator;

Figure 18 is a plan view of the circulator of Figure 17;

Figure 19 is polarisation diagrams for the circulator of Figure 17;

Figure 20 is polarisation diagrams for the circulator of Figure 17 when a first Faraday rotator induces errors;

Figure 21 is polarisation diagrams of the circulator of Figure 17 when a second

Faraday rotator induces errors;

Figure 22 is a side view of a fourth preferred embodiment of an ptical circulator;

Figure 23 is a diagram of the SWP functions of the circulator of Figure 22;

Figure 24 is a plan view of the circulator of Figure 22;

Figure 25 is polarisation diagrams for the circulator of Figure 22;

Figure 26 is polarisation diagrams for the circulator of Figure 22 when Faraday rotators thereof induce errors;

Figure 27 is a side view of a fifth preferred embodiment of an optical circulator;

Figure 28 is a diagram of the SWP function of the circulator of Figure 27;

Figure 29 is a plan view of the circulator of Figure 27;

Figure 30 is polarisation diagrams for the circulator of Figure 27;

Figure 31 is polarisation diagrams for the circulator of Figure 27 when a first Faraday rotator induces errors;

Figure 32 is polarisation diagrams for the circulator of Figure 27 when a second Faraday rotator induces errors; and

Figures 33 and 34 are graphs of isolation v. wavelength for the circulator of Figure 22.

An optical circulator 1, as shown in Figure 1, is a single in-line device or assembly which includes first and third ports 2 and 6 and second and fourth ports 4 and 8 disposed at opposite ends of the assembly 1. The ports 2 to 8 are connected to respective graded refractive index (GRIN) lenses 7 which are used to collimate light to be received by the ports 2 to 8 so that the beam is a predetermined size. Other types of lenses may also be used. The beam width to be handled by the assembly 1 determines the size of the assembly. In some instances the beam width and the assembly 1 may be thin enough that the lenses 7 are not required.

Between the first and third ports 2 and 6 and the second and fourth ports 4 and 8, the isolator 1 comprises an in-line or series assembly of a first SWP 10, a first half-wave plate arrangement 12, a first Faraday/optical rotator 14, a second SWP 16, a second half-wave plate arrangement 18, a third SWP 20, a second Faraday/optical rotator 22, a third half-wave plate arrangement 24 and a fourth SWP 26. The first and third

half-wave plate arrangements 12 and 24 are divided into first, second, third and fourth quadrants 28, 30, 32 and 34, respectively, as shown in the cross-sections of Figures 2 and 3. All cross-sections discussed hereinafter are viewed from end of the first and third ports 2 and 6 of a circulator assembly looking down the length of the assembly to the second and fourth ports 4 and 8.

The first two quadrants 28 and 30 form an upper section 36 and the remaining quadrants 32 and 34 form a lower section 38, as shown in Figure 11. The first and third quadrants 28 and 32 form a left hand side section 40 and the second and fourth quadrants 30 and 34 form a right hand side section 42, as shown in Figure 14. For the first half-wave plate arrangement 12, the second and third quadrants 30 and 32 comprise half-wave plates, whereas the remaining quadrants 28 and 34 include a transmissive medium. The converse is true for the third half-wave plate arrangement 24, as the first and fourth quadrants 28 and 34 include half-wave plates and the second and third quadrants 30 and 32 comprise a transmissive medium.

The half-wave plates rotate incident optical signals by 90° ± m 180° clockwise (m being an integer), i.e. an effective rotation of 90°. The direction of rotation, as with all cross-sections discussed herein, is considered with respect to a view of the circulator assembly from the end of the first and third ports 2 and 6.

The Faraday and optical rotators 14 and 22 each include a Faraday rotator which performs a clockwise 45° ± m 180° rotation on all incident polarised light regardless of the direction of travel, i.e. a non-reciprocal rotation. The rotators 14 and 22 also include an optical rotator which is connected in series with the Faraday rotator and performs a clockwise 45° ± m 180° rotation on incident light travelling in the reverse direction from the second and fourth ports 4 and 8 to the first and third ports 2 and 6 and an anticlockwise 45° ± m 180° rotation on light travelling in the forward direction from the first and third ports 2 and 6 to the second and fourth ports 4 and 8. Therefore light travelling in the forward direction is outputted from the rotator 14 or 22 unchanged, whereas light travelling in the reverse direction is rotated by 90° by the rotator 14 or 22. The first and fourth SWPs 10 and 26 and the rotators 14 and 22 are of a size which

corresponds to that of the first and third half-wave plate arrangements 12 and 24.

The parts 10 to 26 of the assembly 1 are all aligned vertically, as shown in Figure 1, but with reference to the plan view of Figure 4, the first SWP 10, half-wave plate arrangement 12 and rotator 14 form a first part 44, which is offset horizontally with respect to a second part 46, comprising the second rotator 22, the third half-wave plate arrangement 24 and the fourth SWP 26. The first and second parts 44 and 46 are joined by a third part 48 comprising the second half-wave plate arrangement 18 and the second and third SWPs 16 and 20. The second half-wave plate arrangement 18 is wider than the other half-wave plate arrangements 12 and 24 in that it includes three vertical sections 50, 52 and 56, as shown in Figure 4, instead of two vertical sections 40 and 42. The sections 50 to 56 also extend the entire height of the second half-wave plate arrangement 18. The second half-wave plate arrangement is positioned and the first and second parts 44 and 46 of the assembly 1 are arranged so that first vertical section 50 is aligned with the left hand section 40 of the first half-wave plate arrangement 12 and the third vertical section 56 is aligned with the right hand section 42 of the third half-wave plate arrangement 24. The middle vertical section 52 is aligned with the right hand section 42 of the first half-wave plate arrangement 12 and the left hand section 40 of the third half-wave plate arrangement 24. The first SWP 16 is tapered from the first part 44 to the third section 56 of the first half-wave plate arrangement 18. The third SWP 20 is tapered from the first section 50 of the second half-wave plate arrangement 18 to the second part 46 of the assembly 1. The first and third sections 50 and 56 include half-wave plates and the section 52 in between includes a transmissive medium. The first section 50 defines the left hand side of the assembly 1, the second section 52 defines the middle of the assembly and the third section 56 defines the right hand side of the assembly 1.

The assembly 1 will also function correctly, in the same manner, if all elements 10 to 26 are of the same width as the second half-wave plate arrangement 18. The second and third SWPs 16 and 20 would therefore not be tapered.

For light travelling in the forward direction from the first and third ports 2 and

6 to the second and fourth ports 4 and 8, the first SWP 10 splits incident light into horizontal and vertical polarisation components 58 and 59 and walks the horizontal component up a section 36, 38 and leaves the direction of the vertically polarised component unchanged. The fourth SWP 26 walks horizontally polarised components down a section 36, 38 and also leaves the vertically polarised component unchanged. The second SWP 16 walks vertically polarised components across a section 50, 52, 56 to the right and leaves horizontally polarised components unchanged. The third SWP 20 has the same function as the second SWP 16.

The ports 2 to 8 are aligned with the lower sections 38, and the first and fourth ports 2 and 8 are aligned with the middle of the assembly 1. The third port 6 is aligned with the left hand side of the assembly, and the second port 4 is aligned with the right hand side of the assembly.

The optical fibres connected to the GRIN lenses 7 may be slightly offset from the centre of the GRIN lenses so that beams from the fibres are launched into the assembly 1 at a slight angle to avoid reflections appearing on the ports 2 to 8.

The components 10 to 26 may be slightly displaced laterally or vertically with respect to one another to accommodate the launch angle in this case but the assembly 1 functions in the same manner as described.

The paths taken by light through the assembly 1 are illustrated in four polarisation diagrams 60, 62, 64 and 66 of Figure 5 for light incident on the four ports 2 to 8, respectively. The polarisation diagrams 60 to 66 include a series of cross-sectional views of the light components and each of the interfaces of the parts 10 to 26 of the assembly 1. Horizontally polarised components are shown by a horizontal line 58, and vertically polarised components are shown by a vertical line 59. The cross-sections also illustrate the positioning of the light components at each of the interfaces. The same conventions apply for the polarisation diagrams of Figures 6 and 10 to 12.

With reference to the first polarisation diagram 60 of Figure 5, light incident on

the first port 2 is split into horizontal and vertical polarised components by the first SWP 10, the horizontal component being walked up to the upper section 36 of the first half-wave plate arrangement 12. The components are incident n the right hand side 42 of the half-wave plate arrangement 12 such that the upper component is rotated into a vertical plane by the half-wave plate of the second quadrant 30. The two components are passed unaltered by the first rotator 14 and are then walked to the right hand side of the assembly 1 by the second SWP 16. The components are rotated into the horizontal plane by the half-wave plate of the vertical section 56 and are passed unaltered by the second SWP 20 and the second rotator 22. The lower component is rotated into a vertical plane by the half-wave plate of the fourth quadrant 34 of the third half-wave plate arrangement 24 and is passed directly to the second port 4 by the fourth SWP 26. The other component passes through the transmissive medium of the second quadrant 30 of the half-wave plate arrangement 24 and, being horizontally polarised, is walked down by the fourth SWP 26 to be incident on the second port 4.

Light incident on the second port 4 returns via the same path, as shown in the second polarisation diagram 62, until the horizontal components incident on the second rotator 22 are rotated into a vertical plane. The vertically polarised components are walked by the third SWP 20 from the right hand side of the assembly 1 to the middle of the assembly so as to pass through the middle section 52 of the second half-wave plate arrangement 18. The vertically polarised components are then walked by the second SWP 16 to the left hand side of the assembly 1. The components are rotated into a horizontal plane by the first rotator 14 and the lower component is then rotated into a vertical plane by the half-wave plate of the third quadrant 32 of the first half-wave plate arrangement 12. The lower component is passed directly to the third port 6 by the first SWP 10, which walks the upper horizontally polarised component down to the third port 6.

With reference to the third polarisation diagram 64, light incident on the third port 6 is split into an upper horizontally polarised component and a lower vertically polarised component by the first SWP 10 and the lower component is rotated into a horizontal plane by the third quadrant 32 of the first half-wave plate arrangement 12. The two

horizontally polarised components are passed unchanged through the first rotator 14 and the second SWP 16 but are rotated into a vertical plane by the half-wave plate of the vertical section 50 f the second half-wave plate arrangement 18. The vertically polarised components are then walked to the middle of the assembly 1 by the second SWP 20 and are passed by the second rotator 22 to the left hand section 40 of the third half-wave plate arrangement 24. The half-wave plate of the first quadrant 28 rotates the upper component into a horizontal plane, and then the horizontal component is walked down to the lower vertically polarised component by the fourth SWP 26, so as to be both incident on the fourth port 8.

Light received by the fourth port 8, as shown in the fourth polarisation diagram 66, follows the same path as that illustrated in the third polarisation diagram 64 until the vertically polarised components are rotated by the second rotator 22 into a horizontal plane. The horizontally polarised components pass directly through the third and second SWPs 20 and 16 and the middle section 52 of the second half-wave plate arrangement 18. The components are rotated into a vertical plane by the first rotator 14 and the upper component is then rotated into a horizontal plane by the second quadrant 30 of the first half-wave plate arrangement 12. The horizontal component is then walked down towards the vertically polarised component by the first SWP 10 so that both components are incident on the first port 2.

The Faraday rotators in the rotators 14 and 22 used in the circulator are subject to deterioration in performance as the ambient temperature or signal wavelength shifts, which may cause the rotators to inadvertently partially rotate polarised components when travelling in the forward direction. Any errors in the performance of the rotators 14 and 22 can give rise to cross-talk as components incorrectly processed by a rotator 14 or 22 may be directed to a port other than the port for which the light is intended. In situations where it is imperative that cross-talk be minimised and the isolation between ports of a circulator is to be relatively high, any erroneous light components generated by errors induced by a Faraday rotator need to be dissipated by the circulator. The circulator 1 is configured to deal with errors introduced by Faraday rotators and provide relatively high isolation between the ports of the assemblies.

The erroneous components produced by a Faraday rotator can be considered to be polarised in the planes which are orthogonal to the correct planes of polarisation which should be attained for light emitted by the rotator. Therefore, hereinafter the erroneous components are represented as such. Generation of the components can be equated to the rotator to performing another or inverse function to that intended.

Figure 6 includes eight polarisation diagrams, the first four 68, 70, 72 and 74 illustrating the path taken by light incident on the four ports 2 to 8, respectively, when the first rotator 14 introduces errors by inadvertently rotating components travelling in the forward direction, instead of the reverse direction. The remaining four polarisation diagrams 76, 78, 80 and 82 illustrate the path taken by light incident on the four ports 2 to 8, respectively, when the second rotator 22 erroneously rotates components travelling in the forward direction instead of the reverse direction.

With reference to the first polarisation diagram 68 of Figure 6, the vertically polarised components incident on the first rotator 14 are rotated into a horizontal plane and are passed unaltered through the second SWP 16, the middle section 52 of the second half-wave plate arrangement 18, the third SWP 20 and the second rotator 22 so as to be incident on the left hand section 40 of the third half-wave plate arrangement 24. The upper component is rotated into a vertical plane by the first quadrant 28 and is passed unchanged by the fourth SWP 26 to be dissipated above the second and fourth ports 4 and 8. The lower horizontally polarised component is walked out of the assembly 20 by the fourth SWP 26 before reaching the ports 4 and 8. For light incident on the second port, as shown in the second polarisation diagram 70, the vertically polarised components incident on the first rotator 14 are not rotated, and the lower component is then rotated into a horizontal plane by the third quadrant 32 of the first half-wave plate arrangement 12. The horizontally polarised component is walked out of the assembly 1 by the first SWP 10 and the other vertically polarised component is simply passed by the first SWP 10 to be dissipated above first and third ports 2 and 6. With reference to the third polarisation diagram 72, the horizontally polarised components incident on the first rotator 14 are rotated into a vertical plane and are then shifted, first to the middle of the assembly 1 by the second SWP 16 to pass through the middle section 52, and then to the

right hand side of the assembly 1 by th third SWP 20. The components are passed unchanged by the second rotator 22, and the lower component is rotated into a horizontal plane by the fourth quadrant 34 of the third half-wave plate arrangement 24. The upper vertically polarised component is passed by the fourth SWP 26 so as to be dissipated above the second and fourth ports 4 and 8, and the lower horizontally polarised component is walked out of the assembly 1 by the SWP 26 before reaching the ports 4 and 8. For light incident on the fourth port, as shown in the fourth polarisation diagram 74, the horizontally polarised components incident on the first rotator 14 are not rotated and are passed to the right hand section 42 of first half-wave plate arrangement 12. The upper component is rotated by the second quadrant 30 into a vertical plane and is dissipated above the first and third ports 2 and 6 after passing through the first SWP 10. The lower horizontally polarised component is walked out of the assembly 1 by the first SWP 10.

With reference to the fifth polarisation diagram 76 of Figure 6, for light incident on the first port 2 the horizontally polarised components received by the second rotator 22 are rotated into a vertical plane. The upper component passes unchanged through the second quadrant 30 of the third half-wave plate arrangement 24 and is dissipated above the second and fourth ports 4 and 8. The lower component is rotated into a horizontal plane by the fourth quadrant 34 and is walked out of the assembly 1 by the fourth SWP 26. For light incident on the second port 4 as shown in the sixth polarisation diagram 78, the horizontally polarised components incident on the rotator 22 emerge unchanged and are passed by the third SWP 20 to the half-wave plate of the vertical section 56 of the second half-wave plate arrangement 18. The components are rotated into a vertical plane and are then walked across to the middle of the assembly 1 by the second SWP 16. The vertical components are rotated into a horizontal plane by the first rotator 14 and the upper component is then rotated into a vertical plane by the second quadrant 30 of the first half-wave plate arrangement 12. The upper vertically polarised component is passed by the first SWP 10 so as to be dissipated above the first and third ports 2 and 6 and the lower horizontally polarised component is walked out of the assembly 1 before reaching the ports 2 and 6. With reference to the seventh polarisation diagram 80, for light incident on the third port 6 the vertically polarised components incident on the second

rotator 22 are rotated into a horizontal plane and the upper component is rotated back into a vertical plane by the first quadrant 28 of the third half-wave plate arrangement 24. The upper component is passed by the f urth SWP 26 so as to be dissipated above the second and fourth ports 4 and 8. The lower horizontally polarised component is walked out of the assembly 1 before reaching ports 4 and 8. For light incident on the fourth port 8, as shown in the eighth polarisation diagram 82, the vertically polarised components received by the second rotator 22 are not rotated and are a shifted to the left hand side of the assembly 1 by the third SWP 20. The components are rotated into a horizontal plane by the half-wave plate of the first vertical section 50 of the second half-wave plate arrangement 18 and are passed to the first rotator 14 by the second SWP 16. The horizontally polarised components are rotated by the rotator 14 into a vertical plane and the lower component is then rotated into a horizontal plane by the third quadrant 32 of the first half-wave plate arrangement 12. The upper vertically polarised component is passed by the first SWP 10 so as to be dissipated above the first and third ports 2 and 6, and the lower horizontally polarised component is walked out of the assembly 1 by the first SWP 10 before reaching the ports 2 and 6.

The first and third half-wave plate arrangements 12 and 24, and the Faraday/optical rotators 14 and 22 may alternatively be implemented by replacing the rotators 14 and 22 with single Faraday rotators that perform an effective 45° clockwise rotation. The segments 30 and 32 of the first arrangement 12 and the segments 28 and 34 of the third arrangement 24 are then configured with optical rotator material to perform effective 45° clockwise rotations, and the segments 28 and 34 of the first arrangement 12 and the segments 30 and 32 of the third arrangement 24 are provided with optical rotator material configured to perform effective 45° anticlockwise rotations.

A second optical circulator 100, as shown in Figures 7 and 9, is a four port circulator which is also tolerant to rotator errors, yet only requires two half-wave plate arrangements. The circulator 100 includes an in-line assembly of a first SWP 102, a Faraday rotator 104, a first half-wave plate arrangement 106, a first SWP combination 108, a second SWP combination 110, a second half-wave plate arrangement 112, a second Faraday rotator 114 and a second SWP 116. The first and third ports 2 and 6 are

disposed at one end of the assembly abutting the first SWP 102 and the second and fourth ports 4 and 8 are disposed at the opposite end of the assembly abutting the second SWP 116. The ports 2 to 8 are again defined by GRIN lenses 7 which are used to launch light into and receive light from the assembly 100, as discussed previously.

The half-wave plate arrangements 106 and 112 comprise four row sections, 120, 122, 124 and 126 of half-wave plates. The effective optical rotation performed by each row section 120 to 126 is indicated in the cross-sections of Figure 8. Cross-sections marked with +45 perform a clockwise rotation of $45° \pm m\ 180°$, whereas cross-sections marked −45 perform an anticlockwise rotation of $45° \pm m\ 180°$ on polarised components travelling in the forward direction from the first and third ports 2 and 6 to the second and fourth ports 4 and 8. For example the first and bottom section 120 of the first half-wave plate arrangement 106 performs an effective 45° rotation in the anticlockwise direction, whereas the first and bottom section 120 of the second half-wave plate arrangement 112 performs an effective 45° rotation in the clockwise direction.

The functions performed by the two SWPs 102 and 116 and the SWPs sections of the SWP combinations 108 and 110, on light travelling in the forward direction through the assembly 100, is also illustrated in the Figure 8. The arrows in the SWP cross-sections indicate the direction in which polarised components perpendicular to the direction of the arrow are walked away from components polarised in a plane parallel to the direction of the arrow. The first and second SWPs 102 and 116 both walk horizontal components up one row section from vertical components. The first SWP combination 108 is divided into two column sections, a left section 130 and a right section 132. The left column section 130 walks horizontally polarised components down two row sections from vertically polarised components, and the right column section 132 walks horizontally polarised components up two row sections from vertically polarised components. The second SWP combination 110 is divided into a top half SWP section 134 and a bottom half SWP section 136. The SWP half sections 134 and 136 each occupy space equivalent to two row sections 120 and 122 or 124 and 126. The top SWP section 134 walks vertically polarised components, one column section to the right, and the bottom SWP section 136 walks vertically polarised components, one column section to the left.

The Faraday rotators 104 and 114 both perform 45° ± m 180° rotations on polarised components, i.e. an effective clockwise rotati n of 45°.

The first port 2 is aligned with the bottom row section 120, the second port 4 is aligned with the second row section 122, the third port 6 is aligned with the third row section 124, and the fourth port 8 is aligned with the top row section 126. With reference to Figure 9, the first port 2 and the fourth port 8 are aligned with the right hand SWP section 132, and the second port 4 and the third port 6 are aligned with the left hand SWP column section 130.

For the polarisation diagrams of Figures 10 to 12, diagonal lines are used to represent components polarised in a 45°–225° plane and components polarised in a 135°–315° plane, hereinafter referred to as 45° components and 135° components, respectively.

For light incident on the first port 2, as shown in the first polarisation diagram 150 of Figure 10, the first SWP 102 splits the incident light into horizontal and vertical polarisation components, and walks the horizontal component up a row section. The first Faraday rotator 104 rotates the components so they emerge as an upper 135° component and a lower 45° component. The upper component is incident on the second row section 122 of the first half-wave plate arrangement 106, and the lower component is incident on the first row section 120. The sections 120 and 122 rotate both of the components into a vertical polarisation plane. The vertical components are passed unaltered by the first SWP combination 108 to the bottom half 136 of the second SWP combination 110, which walks both of the components across from the right side of the assembly 100 to the left side. The components are then incident on the first and second row sections 120 and 122 of the second half-wave plate arrangement 112 and are rotated into an upper 135° component and a lower 45° component. The upper component is rotated into a vertical component, and the lower component is rotated into a horizontal component by the second Faraday rotator 114. The horizontal component is then walked up to the vertical component by the second SWP 116 so both components are incident on the second port 4.

For light incident on the second port 4, as shown in the second polarisation diagram 152 of Figure 10, the light is split into vertical and horizontal components, with the horizontal component being walked down from the vertical component. The second Faraday rotator 114 rotates the components into an upper 45° component and a lower 135° component, and the components are respectively incident on the second and first row sections 122 and 120 of the second half-wave plate arrangement 112. The second half-wave plate arrangement 112 rotates the components into two horizontally polarised components which are passed unchanged by the second SWP combination 110. The horizontal components are then walked up two row sections to the top of the assembly 100 by the left hand column section 130 of the first SWP combination 108. The components are rotated into an upper 45° component and a lower 135° component by the top row section 126 and the third row section 124, respectively, of the first half-wave plate arrangement 106. The components are then rotated 45° in a clockwise direction by the first Faraday rotator 104 so as to emerge as an upper horizontal component and a lower vertical component. The vertical component is passed unchanged by the first SWP 102 so as to be incident on the third port 6, and the horizontal component is walked down by the first SWP 102 so as to also be incident on the third port 6.

Light incident on the third port 6, as shown in the third polarisation diagram 154 is separated by the first SWP 102 into a lower vertically polarised component and an upper horizontally polarised component which has been walked away from the vertical component. The two components are rotated by the first Faraday rotator 104 into an upper 135° component and a lower 45° component, which are incident on the top row section 126 and the third row section 124 of the first half-wave plate arrangement 106. The components are rotated by the two top sections 124 and 126 of the first half-wave plate arrangement 106 so as to emerge as two vertically polarised components which are passed unaltered by the first SWP combination 108. The upper half 134 of the second SWP combination 110 walks the components across the assembly 100 to the right hand side of the assembly 100. The components are rotated by the upper two row sections 124 and 126 of the second half-wave plate arrangement 112 into an upper 135° component and a lower 45° component. Both components are rotated by the second Faraday rotator 114 so as to emerge as an upper vertical component and a lower horizontal component.

The horizontal component is walked up to the vertical component by the second SWP 116 so that both components are incident on the fourth port 8.

Light incident on the fourth port 8, as shown in the fourth polarisation diagram 156 of Figure 10, is split into an upper vertical component and a lower horizontal component by the second SWP 116. The components are rotated into an upper 45° and a lower 135° component by the second Faraday rotator 114, and are incident on the upper two row sections 124 and 126 of the second half-wave plate arrangement 112. The second half-wave plate arrangement 112 rotates the components into two horizontally polarised components which are passed unaltered by the second SWP combination 110. The components are each walked two row sections down to the bottom of the assembly 100 by the right hand column section 132 of the first SWP combination 108. The components are then incident on the bottom row section 120 and the second row section 122 of the first half-wave plate arrangement 106, which rotate the components into an upper 45° component and a lower 135° component. The first Faraday rotator 104 rotates the components clockwise by 45° so they emerge as an upper horizontally polarised component and a lower vertically polarised component. The vertical component is passed directly to the first port 2 by the first SWP 102, which walks the upper horizontal component down to the first port 2 so as to be incident with the vertical component.

When the first Faraday rotator 104 produces components which appear to be erroneously rotated in the anticlockwise direction, for light incident on the first port 2, as shown in the first polarisation diagram 160 of Figure 11, a 45° component and a 135° component are incident on the second row section 122 and the bottom row section 120, respectively, of the first half-wave plate arrangement 106. The bottom two sections 120 and 122 of the first half-wave plate arrangement 106 rotate the components into an upper horizontal component and a lower horizontal component. The horizontal components are walked up to row sections to the top of the assembly 100 by the right hand column section 132 of the first SWP combination 108, and are allowed to pass unchanged by the second SWP combination 110. The top row section 126 and the third row section 124 of the second half-wave plate arrangement 112 rotates the components into an upper 45° component and a lower 135° component. The components are then rotated by the second

Faraday rotator 114 into an upper horizontally polarised component and a lower vertical component. The vertical component is passed unaltered by the second SWP 116 and is dissipated between the second port 4 and the fourth port 8. The second SWP 116 walks the horizontally polarised component out of the assembly 100 above the fourth port 8. The components are also dissipated to the right hand side of the second port 4. For light travelling in the reverse direction from the second port 4 towards the third port 6, as shown in the second polarisation diagram 162 of Figure 11, the first Faraday rotator 104 emits an erroneous upper vertically polarised component and a lower horizontal component. The vertical component is passed directly by the first SWP 102 so as to be dispersed above the third port 6, and the horizontal component is walked by the first SWP 102 downwards so as to be dispersed between the first and third ports 2 and 6. For light travelling from the third port 6, as shown in the third polarisation diagram 164 of Figure 11, the first Faraday rotator 104 emits an upper 45° component and a lower 135° component which are incident on the top row section 126 and the third row section 124 of the first half-wave plate arrangement 106. The row sections 126 and 124 rotate the components into two horizontally polarised components, which are walked down two row sections to the bottom of the assembly 100 by the left hand SWP column section 130 of the first SWP combination 108. The components are passed unaltered by the second SWP combination 110, and are then rotated by the bottom two row sections of the second half-wave plate arrangement 112 into an upper 45° component and a lower 135° component. The 45° component is rotated into a horizontal component by the second rotator 114 and the 135° component is rotated into a vertical component. The horizontal component is walked up a row section by the second SWP 116 and the vertically polarised component is allowed to pass unchanged, such that both components are dissipated below and to the left of the fourth port 8. The horizontal component passes above and the vertical component below the second port 4. For light incident on the fourth port 8, as shown in the fourth polarisation diagram 166 of Figure 11, the first Faraday rotator 104 emits an upper vertically polarised component and a lower horizontally polarised component. The vertical component is passed by the first SWP 102 unaltered so as to be dissipated between the first and third ports 2 and 6, whereas the SWP 102 walks the horizontally polarised component out of the assembly 100 below the first port 2.

When the second Faraday rotator 114 produces components which appear to be erroneously rotated in the anticlockwise direction, for light incident on the first port 2, as shown in the first polarisation diagram 168 of Figure 12, the second rotator 114 emits an upper horizontally polarised component and a lower vertically polarised component. The vertically polarised component is passed unchanged by the second SWP 116 so as to be dispersed below both the second and fourth ports 4 and 8, and the horizontally polarised component is walked up by the first SWP 116 so as to be dispersed between the second and fourth ports 4 and 8. For light incident on the second port, as shown in the second polarisation diagram 170 of Figure 12, the second Faraday rotator 114 emits an upper 135° component and a lower 45° component which are rotated into two vertically polarised components by the lower sections 120 and 122 of the second half-wave plate arrangement 112. The vertically polarised components are shifted across to the right hand side of the assembly 100 by the bottom section 136 of the second SWP combination 110, and are allowed to pass unaltered by the first SWP combination 108. The bottom row sections 120 and 122 of the first half-wave plate arrangement rotate the components into an upper 135° component and a lower 45° component, and the two components are rotated into an upper vertical component and a lower horizontal component by the first rotator 104. The lower horizontal component is walked out of the assembly 100 by the first SWP 102 so as to be dispersed below the first port 2, and the vertical component passes unchanged so as to be dispersed between the first port 2 and the third port 6. For light incident on the third port 6, as shown in the third polarisation diagram 172 of Figure 12, the second rotator produces an erroneous upper horizontally polarised component and lower vertical component. The horizontal component is walked out of the assembly 100 above the fourth port 8, and the lower vertical component is allowed to pass unaltered by the second SWP 116 so as to be dispersed between the second and fourth ports 4 and 8. For light incident on the fourth port 8, as shown in the fourth polarisation diagram 174 of Figure 12, the second rotator 114 produces an upper 135° component and a lower 45° component which are rotated into two vertically polarised components by the upper sections 124 and 126 of the first half-wave plate arrangement 112. The vertically polarised components are shifted across to the left hand side of the assembly 100 by the upper SWP section 134 of the second SWP combination 110, and are allowed to pass unaltered by the first SWP combination 108. The upper row

sections 124 and 126 of the first half-wave plate arrangement 106 rotate the components into an upper 135° component and a lower 45° component. The first Faraday rotator 104 rotates the components 45° clockwise so as to produce an upper vertical component and a lower horizontal component. The vertical component is passed unchanged by the first SWP 102 so as to be dispersed above the third and first ports 6 and 2, whereas the horizontal component is walked down by the first SWP 102 so as to be dispersed between the first and third ports 2 and 6.

Both of the circulators 1 and 100 are tolerant to rotator errors and do not require segmented Faraday rotators. The second circulator 100 is also not subject to polarisation dispersion. Polarisation dispersion can occur in circulator configurations when the polarised components travel different distances in a circulator assembly between input and output ports 2 to 8. The components of light incident on ports 2 to 8 of the second circulator 100 travel the same distance between ports 2 to 8. The half-wave plate sections 120, 122, 124 and 126 are selected so that dispersion induced by the first arrangement 106 is compensated or cancelled by dispersion induced by the second arrangement 112. A half-wave plate induces polarisation dispersion as an incident polarised component is processed as two further components parallel and perpendicular to the half-wave plate's optical axis and it is the different treatment of these two further components which gives rise to dispersion. Polarisation dispersion in the first circulator 1 can be improved by rotating the end SWP 26 and the ports 4 and 6 by 180° and reconfiguring the third half-wave plate arrangement 24, accordingly.

A laboratory configuration of the first circulator 1 is illustrated in Figure 13 having a single input GRIN lens 7 connected to the first port 2 of the circulator 1 and an infrared camera 180 mounted to receive all light output by the circulator 1 from the fourth SWP 26. With light incident on the first port 2, Figure 14 illustrates the incident light as correctly output at the position of the second port 4. To simulate errors which may be induced by the Faraday rotators 14 and 22 of the circulator, the half-wave plates of the arrangements 12, 18 and 24 were adjusted so as to be misaligned. Adjusting the half-wave plates so as to simulate an error in the first rotator 14, Figure 15 illustrates that the majority of light was passed to the position of the second port, and erroneous

components were dissipated above and below the position of the fourth port 8. Negatives obtained from the camera 180 have been inverted so as to produce photographs which correspond to the direction of view convention used in the polarisation diagrams 70 and 76. Adjusting the half-wave plates to simulate an error in the second rotator, Figure 16 illustrates the majority of incident light is output at the position of the second port 2 with the erroneous components being dissipated above and below the position of the second port 2.

A third optical circulator 202, as shown in Figures 17 and 18, includes first and third ports 204 and 208 disposed at one end, a second port 206 disposed at the opposite end, and a series in-line assembly of parts including a first spatial walk-off polariser (SWP) 210, a first Faraday rotator 212, an SWP combination 214, a second Faraday rotator 216 and a second SWP 218. The SWP combination 214 includes upper and lower SWP sections 220 and 222, as shown in Figure 17. The ports 204 to 208 are aligned with the lower section 222, with the first and third ports 204 and 208 being spaced apart and abutting the first SWP 210, as shown in Figure 18. The second port 202 abuts the second SWP 218, and is aligned with the third port 208. The first port 204 is aligned with the right hand side of the assembly 202, as shown in Figure 18. Graded refractive index (GRIN) lenses 224 define each port and are used to launch light into and receive light from the circulator 202. To minimise insertion loss and offset reflections, the launch angle of light into the circulator from the GRIN lenses 224 is set so that the reflected light from the interfaces of the parts of the assembly 202 do not impinge on any of the ports 204, 206 or 208.

The SWPs 210 and 218 are orientated so as to separate incident light into two diagonal polarisation planes, a 45°–225° plane and a 135°–315° plane, and the polarised components are hereinafter referred to as the 45° component and the 135° component, respectively. The first SWP 210 walks the 45° component away from the 135° component in a direction parallel to the 135° component for incident light travelling in the forward direction from the first port 204 to the second port 206. The second SWP 218 walks the 135° component away from the 45° component in a direction parallel to that of the 45° component for incident light travelling in the reverse direction from the

second port 206 t the third port 208. Reciprocal functions are performed for light travelling in the opposite direction. The Faraday rotators 212 and 216 each rotate polarised components by an effective 45°, i.e. 45° ± m 180° where m is a positive integer, in the clockwise direction.

The upper section 220 of the SWP combination 214 is orientated so as to walk vertically polarised components of light travelling in the forward direction across the assembly 202 towards the right hand side of the assembly 202. The lower section 222 of the SWP combination 214 is arranged so as to perform the opposite operation to the upper section, in that vertical components of light travelling in the forward direction are walked across the assembly 202 towards the left hand side of the assembly 202. Horizontal components pass unchanged through the sections 220 and 222. The SWP combination 214 performs reciprocal operations on polarised components travelling in the reverse direction.

The manner in which the polarised components of light incident on the assembly 202 move through the assembly is illustrated in the polarisation diagrams of Figures 19 to 21. The polarisation diagrams again adopt the convention of illustrating the position of polarisation components at the cross-section of each interface between the parts 210 to 218 of the assembly. The cross-sections are viewed from the end of the assembly 202 which includes the first port 204. The same convention is adopted for the polarisation diagrams of Figures 25, 26, 30, 31 and 32.

Light incident on the first port 204 of the circulator 202, as shown in the first polarisation diagram 226 of Figure 19, is separated into 45° and 135° components by the first SWP 210, and only the 45° component is walked diagonally up so as to be aligned with the upper section 220. The components are rotated by the first Faraday rotator 212 so as to be incident on the SWP combination 214 as an upper horizontal component and a lower vertically polarised component. The vertically polarised component is shifted across to the left of the assembly by the lower section 222 so as to be aligned with the second port 206 instead of the first port 204. The components are again rotated by 45° by the second Faraday rotator 216 so that the upper component becomes a 135°

component the lower component becomes a 45° component. The upper component is then walked diagonally down to the lower component by the second SWP 218 so as to be incident on the second port 206. Light incident on the second port 206, as shown in the second diagram 228 of Figure 19, is split into a 45° and a 135° component by the second SWP 218, and the 135° component is walked diagonally up so as to be aligned with the upper section 220. The components are rotated by the second rotator 216 into an upper vertical component and a lower horizontal component. The vertical component is walked across to the left hand side of the assembly 202 by the upper section 220 of the SWP combination 214, then the two components are rotated by the first rotator 212 into an upper 45° component and a lower 135° component. The upper component is then walked diagonally down by the first SWP 210 so as to be incident with the lower component on the third port 208.

The optical circulator 202 is advantageously tolerant to errors induced by the Faraday rotators 212 and 216 in that erroneous components produced by the rotators 212 and 216 do not appear at the ports 204, 206 and 208.

For instance, when the first Faraday rotator 212 produces components rotated in the anticlockwise direction instead of the clockwise direction when light is incident on the first port 204, the first Faraday rotator 212 emits an upper vertical component and a lower horizontal component, as shown in the first polarisation diagram 230 of Figure 20. The upper vertical component is incident on the SWP combination 214 and is walked out of the assembly 202 by the upper section 220. The lower horizontal component proceeds to the second rotator 216, is rotated into the 135° plane and is then walked out of the assembly 202 by the second SWP 218. The erroneous components therefore do not appear at the second port 206.

Figures 20 and 31 illustrate movements of components after they have been walked out of the assembly 202 for situations where the parts 210 to 218 of the assembly 202 have a larger cross-sectional area than illustrated in the Figures. The illustrated paths travel of these components show that even for larger cross-sections of the assembly parts 210 to 218, the erroneous polarisation components are not incident on the ports 204,

206 and 208.

For light incident on the second port 206, as shown in the second polarisation diagram 232 of Figure 20, errors induced by the first Faraday rotator 212 produce an upper 135° and a lower 45° component. The lower component is walked out of the assembly 202 by the first SWP 210, and the upper component is simply dissipated above the first and third ports 204 and 208.

When the second Faraday rotator 216 produces erroneous components rotated anticlockwise instead of clockwise, for light incident on the first port 204, as shown in the first polarisation diagram 234 of Figure 21, an upper 45° component and a lower 135° component are emitted from the rotator 216. The upper component is passed unchanged by the second SWP 218 so as to be dissipated above the second port 206, and the lower component is walked out of the assembly 202 by the second SWP 218 below the second port 206. For light travelling in the reverse direction from the second port 206, as shown in the second polarisation diagram 236 of Figure 21, the second rotator 216 emits an upper horizontally polarised component and a lower vertically polarised component. The upper component passes unchanged through the SWP combination 214, but the lower vertical component is shifted across to the right side of the assembly 202 by the lower SWP section 222. The components are rotated into an upper 135° component and a lower 45° component by the first rotator 212. The upper component is then passed by the first SWP unchanged so as to be dissipated above the first and third ports 204 and 208, and the lower 45° component is walked out of the assembly 202 below the ports 204 and 208 by the first SWP 210.

A fourth optical circulator 240, as shown in Figures 22 and 24, also includes first and third ports 204 and 208, and a second port 206 disposed at opposite ends of an in-line assembly. Between the first and third ports 204 and 208, and the second port 206 is a first SWP 242, a first Faraday rotator 244, a first SWP combination 246, a second SWP combination 248, a second Faraday rotator 250, and a second SWP 252. The Faraday rotators 244 and 250 both perform an effective 45° clockwise rotation of polarised components incident thereon. The first SWP combination 246, as shown in

Figure 24, is divided int  a left hand side SWP section 254 and a right hand side SWP section 256. The second SWP combination is divided into an upper SWP section 258 and a lower SWP secti n 260. The SWP functions performed by the SWPs 242 and 252 and the SWP sections 254 to 260, for light travelling in the forward direction from the first port 204 to the second port 206, is illustrated by the arrows in the cross-sections of Figure 23, which are viewed from the end of the first and third ports 204 and 208. The arrows indicate the direction in which a polarisation component perpendicular to the arrow is walked. A polarisation component parallel to the arrow is allowed to pass unchanged. The reciprocal function, which can be indicated by reversing the direction of the arrows in Figure 23, is performed on components travelling in the reverse direction from the second port 206 to the third port 208.

The first port 204 is aligned with the bottom half of the upper SWP section 258, and the right hand half of the right hand SWP section 256. The second port 206 is aligned with the upper half of the lower SWP section 260, and the left hand half of the right hand section 256. The third port 208 is aligned with the bottom half of the lower section 260, and the right hand half of the left hand SWP section 254. GRIN lenses 224 are used to define the ports 204 to 208 and are used to launch light into the assembly 240 at an angle which prevents reflections from the interfaces of the parts 242 to 252 of the assembly 240 from impinging on any of the ports 204, 206 or 208.

The fourth circulator 240, like the third circulator 202, does not include any wave plates and also is tolerant to errors induced by the rotators 244 and 250. The fourth circulator 240 is, however, also not subject to spatial dispersion of the polarised components which pass through the assembly, as the distance travelled through the assembly 240 by two polarised components of light incident on the assembly 240 is the same for each component, as illustrated in Figure 25.

Light incident on the first port 204, as shown in the first polarisation diagram 262 of Figure 25, is split into a 45° component and a 135° component by the first SWP 242, and the 45° component is walked diagonally up from the 135° component. The two components are rotated into an upper horizontal component and a lower vertical

component by the first rotator 244 and are both incident on the right hand SWP section 256 of the first combination 246. The horizontally polarised component is walked down by the right hand section 256 to the lower section 260 of the second combination 248, and the vertical component passes unchanged to the upper section 258. The vertical component is walked across to the left of the assembly by the upper section 258 and the horizontal component passes unchanged to the second rotator 250. The vertical component is rotated into a 45° component and the horizontal component into a 135° component by the second rotator 250. The second SWP 252 passes the 135° component unchanged to the second port 206, and walks the 45° component diagonally down to the right so as to be incident on the second port 206 with the 135° component.

Light incident on the second port 206, as shown in the second polarisation diagram 264 of Figure 25, is split into a 45° component and a 135° component, with the 45° component being walked diagonally up to the left from the other component. The two components are rotated by the second rotator 250 so that a horizontal component is incident on the upper section 258, and a vertical component incident on the lower section 260 of the second SWP combination 248. The horizontal component passes unchanged to the left hand section 254 of the first combination 246, and the vertical component is walked across to the left of the assembly so as to be also incident on the left hand section 254. The left hand section 254 passes the vertically polarised component unaltered to the first rotator 244, but walks the horizontal component down to the bottom of the assembly 240. The vertical and horizontal components are rotated into 45° and 135° components, respectively, by the second rotator 244. The 135° component passes unchanged through the first SWP 242 to the third port 208, and the 45° component is walked diagonally down to the third port 208 so to be incident thereon with the other component.

When the first Faraday rotator 244 erroneously produces components rotated in an anticlockwise direction by 45°, for light travelling in the forward direction, as shown in the first polarisation diagram 266 of Figure 26, the first rotator 244 produces an upper vertical component and a lower horizontal component which are both incident on the right hand section 256 of the first combination 246. The horizontal component is walked down to the bottom of the assembly 240 by the right hand section 256 and the vertical

component passes unchanged to the upper section 258 of the second combination 248. The vertical component is then walked across to the left hand side of the assembly 240 by the upper section 258. The horizontal component passes through the lower section 260 unchanged. The vertical and horizontal components are rotated by the second rotator 250 into 45° and 135° components, respectively. The 135° component passes through the second SWP 252 so as to be dispersed below the second port 206, and the 45° component is walked diagonally down towards the second port 206 but is still dispersed above and to the left hand side of the port 206. In the reverse direction, as shown in the second polarisation diagram 268 of Figure 26, the first rotator 244 produces an upper 135° component and a lower 45° component. The upper component is dispersed between and to the left hand side of the first and third ports 204 and 208, and the 45° component is walked out of the assembly 240 by the first SWP 242.

When the second Faraday rotator 250 generates components erroneously rotated in an anticlockwise direction, for light travelling in the forward direction, as shown in the third polarisation diagram 270 of Figure 26, the rotator 250 emits a 135° component which is passed unchanged by the second SWP 252 so as to be dispersed above and to the left of the second port 206, and a 45° component aligned with the second port 206. The 45° component is walked diagonally down by the second SWP 252 so as to be dispersed below and to the right of the second port 206. For light travelling in the reverse direction, as shown in the fourth polarisation diagram 272 of Figure 26, the rotator 250 emits a vertical component which is incident on the upper SWP section 258, and a horizontal component which is aligned with the right hand section 256 of the first SWP combination 246. The vertical component is walked across to the right hand side of the assembly 240 by the second combination 248, and the horizontal component is walked up to the top of the assembly 240 by the first combination 246. The horizontal and vertical components are rotated into 135° and 45° components, respectively, by the first rotator 244. The 135° component passes unchanged above the first and third ports 204 and 208, and the 45° component is walked out of the assembly 240.

A fifth optical isolator 280, as shown in Figures 27 and 29, provides for a slightly smaller assembly than that of the fourth isolator 240. The fifth isolator 280 also does not

include any wav plates, has a tolerance to Faraday rotator errors, and is not subject to spatial dispersion of polarisation components. The assembly 280 has first and third ports 204 and 208 at one end, a second port 206 at the other, between which is disposed a first SWP 282, a first Faraday rotator 284, a first SWP combination 286, a second SWP combination 288, a second Faraday rotator 290 and a second SWP 292. The Faraday rotators 284 and 290 perform effective 45° clockwise rotations of polarisation components, and the functions performed by the SWPs 282 and 292 and the SWP sections 296, 298, 302 and 304 of the combinations 286 and 288 are indicated, as in Figure 23, by the arrows in the cross-sections of Figure 28 for light travelling in the forward direction from the first port 204 to the second port 206. The combinations 286 and 288 are divided diagonally into two equal sections. The first combination 286 is divided by a 135°-315° plane 294 into a left hand section 296 and a right hand section 298. The second combination 288 is divided by a 45°-225° plane 300 into a left hand section 302 and a right hand section 304. The SWPs 282 and 292 and the SWP sections 296, 298, 302 and 304 perform a reciprocal functions on light travelling in the reverse direction from the second port 206 to the third port 208.

The ports 204 to 208 are all aligned with the bottom or lower half of the assembly 280, as shown in Figure 27. The first port 204 is aligned with the right hand side of the assembly 280, the third port 208 is aligned with the left hand side of the assembly 280, and the second port 206 is aligned with the middle of the assembly 280, as shown in Figure 29.

For the circulator 280 to function correctly and prevent inadvertent overlap of polarisation components as they pass through the assembly 280, the walk-off distance produced by the walk-off sections 296 to 304 should be at least $b\sqrt{2}$, where b is the diameter of the light beams incident on the ports 204 to 208. The ports 204 to 208 are defined, again, by GRIN lenses 224 which launch light into the assembly 280 at an angle which prevents reflections from the interfaces of the ports 282 to 292 from impinging on any of the ports 204, 206 or 208. The beam diameter, b, is slightly less than the diameter of the GRIN lenses 224.

For light travelling in the forward direction, as shown in the first polarisation diagram 106 of Figure 30, light incident n the first port 204 is split into horizontal and vertically polarised components, with the horizontal component being walked up from the vertical component by the first SWP 282. The components are rotated into 135° and 45° components by the first rotator 284 and are incident on the right hand SWP section 298 of the first combination 286. The 45° component is walked diagonally up by the first combination 286 to the upper middle of the assembly 280, and then the 135° component is walked diagonally down to the lower middle of the assembly 280 by the second SWP combination 288. The second rotator 290 receives the upper 45° component and the lower 135° component and rotates them into horizontal and vertical components, respectively. The horizontal component is then walked down by the second SWP 292 so as to be incident on the second port 206 with the vertical component.

Light incident on the second port 206, as shown in the second polarisation diagram 108 of Figure 30, is split into horizontal and vertical polarisation components, with the horizontal component being walked up from the vertical component. The second Faraday rotator 290 rotates the horizontal and vertical components into 135° and 45° components, respectively, and the 135° component is incident on the left hand section 302 of the second combination 288, which walks the component diagonally down towards the left bottom corner of the assembly 280. The 45° component passes unchanged through the second combination 288 to the left hand section 296 of the first combination 286, where the component is walked diagonally up to the left hand top corner of the assembly 280. The 45° and 135° components are rotated by the first rotator 284 into horizontal and vertical components, respectively. The vertical component is passed by the first SWP 282 directly to the third port 208, and the horizontal component is walked diagonally down by the first SWP 282 so as to also be incident on the third port 208.

When the first Faraday rotator 284 produces components rotated in the anticlockwise direction by 45°, instead of the clockwise direction, for light incident on the first port 204, as shown in the first polarisation diagram 110 of Figure 31, an upper 45° component and a lower 135° component are incident on the first combination 286 at the right hand side of the assembly 280. The upper 45° component is walked diagonally

out of the assembly by the right hand section 298 of the first combination 286, and the 135° component passes to the right hand section 304 of the second combination 288, which walks the 135° component diagonally out of the assembly. For light incident on the second port, as shown in the second polarisation diagram 112 of Figure 31, the first rotator 284 emits an upper vertical component and a lower horizontal component at the left hand side of the assembly 280. The vertical component is passed by the first SWP 282 so as to be dispersed above the first and third ports 204 and 208, and the lower horizontal component is walked out of the assembly 280 by the first SWP 282 before reaching the ports 204 and 208.

When the second Faraday rotator 290 produces erroneous components rotated anticlockwise instead of clockwise, for light travelling in the forward direction, as shown in the first polarisation diagram 114 of Figure 32, the rotator 290 emits an upper vertical component and a lower horizontal component aligned with the middle of the assembly 280. The vertical component is passed by the second SWP 292 unchanged so as to be dispersed above the second port 206, and the lower component is walked out of the assembly 280 by the SWP 292 before reaching the second port 206. For light incident on the second port 206, as shown in the second polarisation diagram 116 of Figure 32, the second rotator 290 emits an upper 45° component and a lower 135° component. The lower 135° component is walked diagonally up to the right hand top corner of the assembly 280 by the right hand section 304 of the second combination 288. The 45° component is then walked diagonally down to the right hand bottom corner of the assembly 280 by the right hand section 298 of the first SWP combination 286. The 135° component and the 45° component are rotated by the first rotator 284 into an upper vertical component and a lower horizontal component, respectively. The upper vertical component is passed by the first SWP 282 so as to be dispersed above the first and second ports 204 and 208, and the SWP 282 walks the horizontal component out of the assembly 280 before reaching the ports 204 and 208.

Figures 33 and 34 illustrate isolation measurements obtained using the fourth optical circulator 240. Figure 33 is a graph of the isolation measured as a function of wavelength for light input on the third port 208 and output from the second port 206.

Figure 34 is a graph of the isolation measured as a function of wavelength for light incident on the second port 206 and output from the first port 208.

For light incident on the first port 204 and outputted from the second port 206, polarisation dispersion has been measured at 0.04 picoseconds.

For light incident on the second port 206 and output from the third port 208, polarisation dispersion has been measured at 0.06 picoseconds.

Insertion loss has been measured at being within a range of 0.6 dB to 1.0 dB for the ports 204, 206 and 208 of the fourth circulator 240. Two uncoated SWP interfaces were used and account for approximately 0.35 dB of the insertion loss. The losses do not include any losses associated with use of the GRIN lenses 224.

CLAIMS:

1. An optical circulator including at least four ports, polariser means, reciprocal rotator means, and Faraday rotators, said circulator being substantially tolerant to errors induced by said Faraday rotators and adapted to operate as a four port circulator.

2. An optical circulator as claimed in claim 1, wherein at least one of said Faraday rotators is formed from one piece of Faraday material.

3. An optical circulator as claimed in claim 1, comprising an in-line assembly of said polariser means, said reciprocal rotator means and said Faraday rotators.

4. An optical circulator as claimed in claim 3, wherein at least one of said Faraday rotators is disposed between one of said reciprocal rotator means and one of said polariser means.

5. An optical circulator as claimed in claim 3, wherein at least one of said reciprocal rotator means is disposed between one of said polariser means and one of said Faraday rotators.

6. An optical circulator as claimed in claim 3, wherein said reciprocal rotator means includes a plurality of light receptive sections, said sections alternately comprising optical rotating material and a transmissive medium.

7. An optical circulator as claimed in claim 6, wherein said sections are quadrants of said reciprocal rotator means.

8. An optical circulator as claimed in claim 7, wherein said optical rotating material rotates incident light $90° \pm m\,180°$, m being an integer.

9. An optical circulator as claimed in claim 3, wherein said reciprocal rotator means includes a plurality of light receptive sections, said sections comprising four rows of

optical rotating material.

10. An optical circulator as claimed in claim 9, wherein said rows rotate incident light 45° ± m 180° clockwise and anticlockwise, alternately, m being an integer.

11. An optical circulator as claimed in claim 3, wherein the ports of the circulator are formed on at least one of said polariser means.

12. An optical circulator as claimed in claim 3, comprising two of said Faraday rotators, one disposed with one of said reciprocal rotator means between a first one of said polariser means and a second one of said polariser means, and the other disposed with a second one of said reciprocal rotator means between third and fourth ones of said polariser means.

13. An optical circulator as claimed in claim 12, including a third one of said reciprocal rotator means disposed between the second and third polariser means.

14. An optical circulator as claimed in claim 12, wherein the Faraday rotators rotate light received from a forward or reverse direction 45° ± m 180°, m being a positive integer.

15. An optical circulator as claimed in claim 12, wherein the Faraday rotators are each combined with an optical rotator so as to rotate light received from one direction 90° ± m 180° and output light received from the opposite direction unaltered, m being an integer.

16. An optical circulator as claimed in claim 1, wherein said polariser means comprises at least one spatial walk–off polariser.

17. An optical circulator having at least three ports and consisting of polariser means and Faraday rotators, said circulator being adapted to operate as a three port circulator.

18. An optical circulator as claimed in claim 17, being tolerant to errors induced by said rotators.

19. An optical circulator as claimed in claim 17, wherein at least one of said Faraday rotators is formed from one piece of Faraday material.

20. An optical circulator as claimed in claim 17, comprising an in-line assembly of said polariser means and said rotators.

21. An optical circulator as claimed in claim 20, wherein said Faraday rotators are disposed between pairs of said polariser means.

22. An optical circulator as claimed in claim 20, comprising a series assembly of a first polariser means, a first Faraday rotator, a second polariser means, a second Faraday rotator and a third polariser means.

23. An optical circulator as claimed in claim 22, wherein the second polariser means comprises different upper and lower light receptive sections.

24. An optical circulator as claimed in claim 22, wherein said second polariser means comprises two polarisers arranged in series in said assembly, each including different light receptive sections.

25. An optical circulator as claimed in claim 17, wherein said polariser means includes at least one spatial walk-off polariser.

26. An optical circulator as claimed in claim 17, wherein the ports of the circulator are formed on at least one polariser means.

27. An optical circulator as claimed in claim 20, wherein said Faraday rotators rotate light received in a forward or reverse direction $45° \pm m\ 180°$, m being an integer.

AMENDED CLAIMS

[received by the International Bureau on 30 March 1994 (30.03.94); original claim 17 amended; original claim 19 deleted; remaining claims unchanged (2 pages)]

optical rotating material.

10. An optical circulator as claimed in claim 9, wherein said rows rotate incident light 45° ± m 180° clockwise and anticlockwise, alternately, m being an integer.

11. An optical circulator as claimed in claim 3, wherein the ports of the circulator are formed on at least one of said polariser means.

12. An optical circulator as claimed in claim 3, comprising two of said Faraday rotators, one disposed with one of said reciprocal rotator means between a first one of said polariser means and a second one of said polariser means, and the other disposed with a second one of said reciprocal rotator means between third and fourth ones of said polariser means.

13. An optical circulator as claimed in claim 12, including a third one of said reciprocal rotator means disposed between the second and third polariser means.

14. An optical circulator as claimed in claim 12, wherein the Faraday rotators rotate light received from a forward or reverse direction 45° ± m 180°, m being a positive integer.

15. An optical circulator as claimed in claim 12, wherein the Faraday rotators are each combined with an optical rotator so as to rotate light received from one direction 90° ± m 180° and output light received from the opposite direction unaltered, m being an integer.

16. An optical circulator as claimed in claim 1, wherein said polariser means comprises at least one spatial walk-off polariser.

17. (Amended) An optical circulator, without reciprocal rotator means, having at least three ports, polariser means and Faraday rotators, at least one of said Faraday rotators being formed from one piece of Faraday material and said circulator being

adapted to perate as a three port circulator.

18. An optical circulator as claimed in claim 17, being tolerant to errors induced by said rotators.

19. (Deleted)

20. An optical circulator as claimed in claim 17, comprising an in-line assembly of said polariser means and said rotators.

21. An optical circulator as claimed in claim 20, wherein said Faraday rotators are disposed between pairs of said polariser means.

22. An optical circulator as claimed in claim 20, comprising a series assembly of a first polariser means, a first Faraday rotator, a second polariser means, a second Faraday rotator and a third polariser means.

23. An optical circulator as claimed in claim 22, wherein the second polariser means comprises different upper and lower light receptive sections.

24. An optical circulator as claimed in claim 22, wherein said second polariser means comprises two polarisers arranged in series in said assembly, each including different light receptive sections.

25. An optical circulator as claimed in claim 17, wherein said polariser means includes at least one spatial walk-off polariser.

26. An optical circulator as claimed in claim 17, wherein the ports of the circulator are formed on at least one polariser means.

27. An optical circulator as claimed in claim 20, wherein said Faraday rotators rotate light received in a forward or reverse direction 45° ± m 180°, m being an integer.

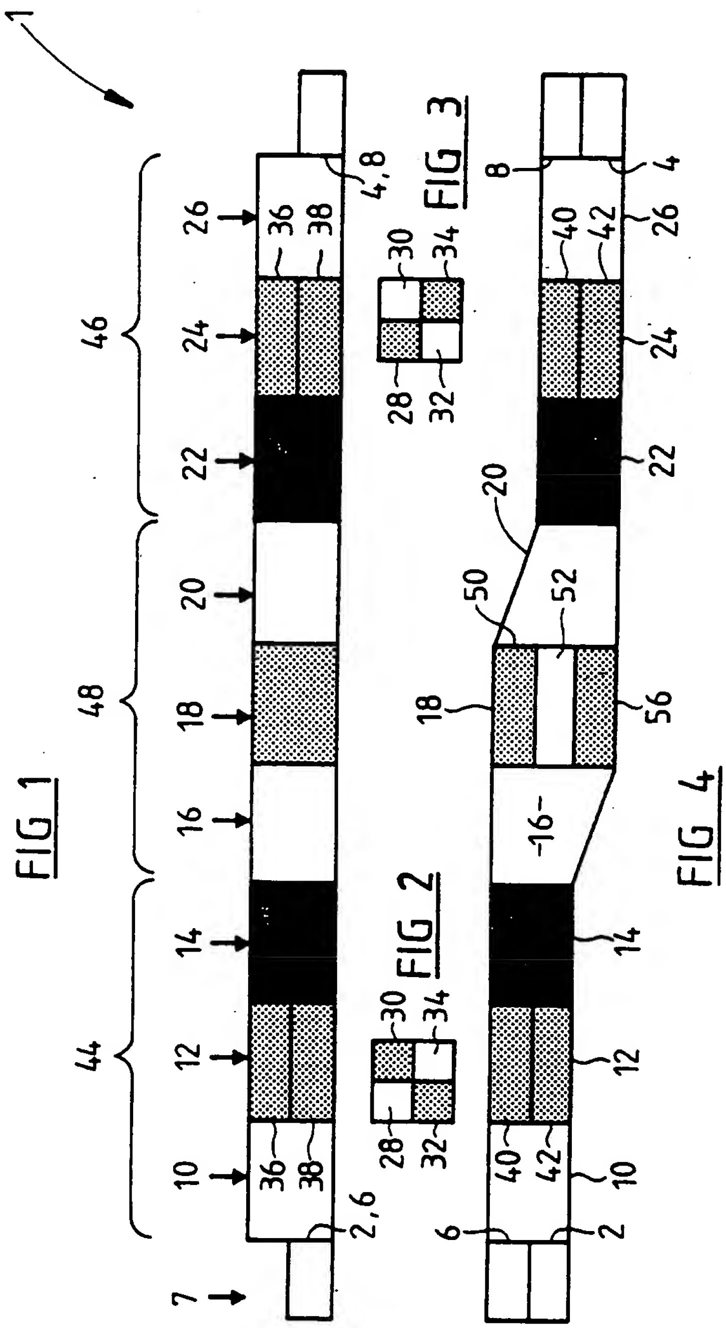


FIG 1
FIG 2
FIG 3
FIG 4

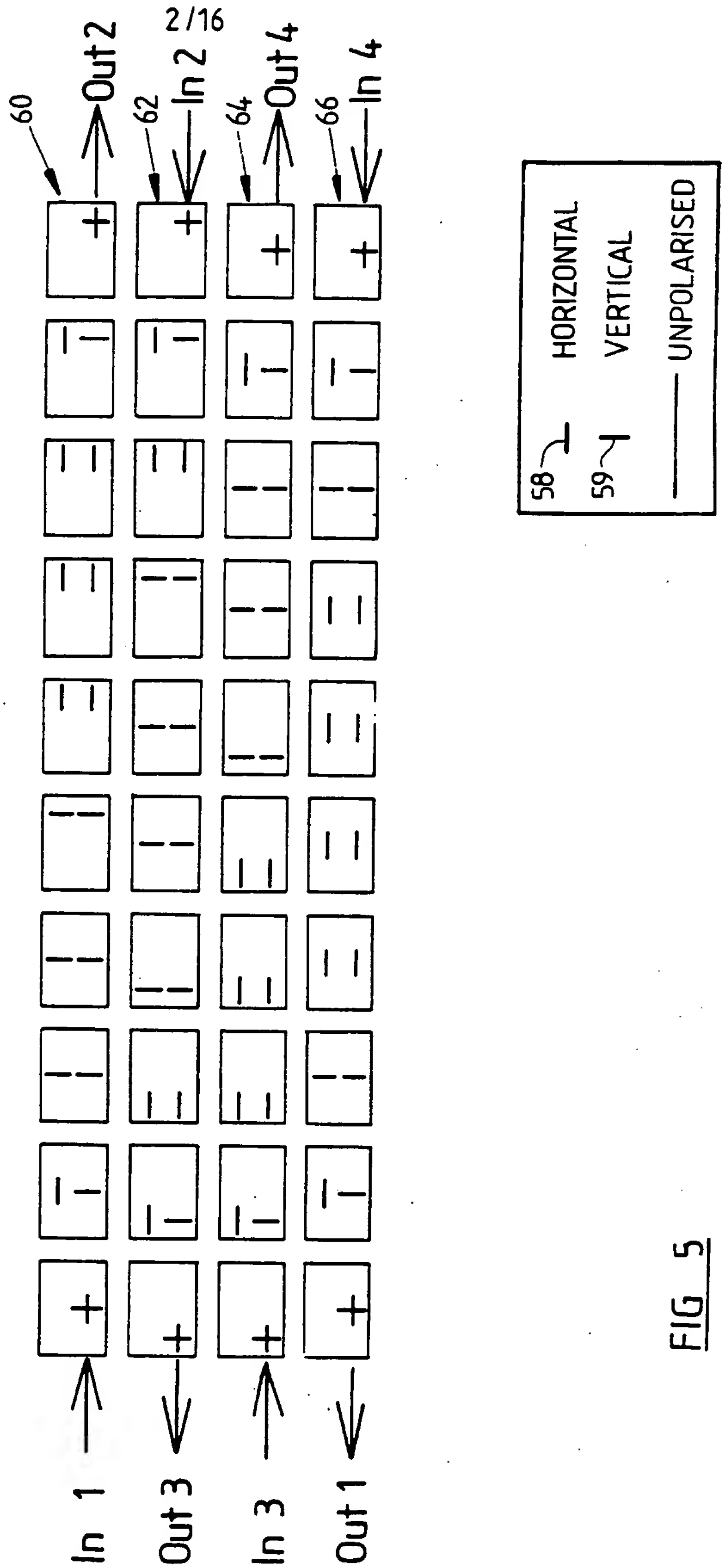

60
Out 2
62
In 2
64
Out 4
66
In 4
In 1
Out 3
In 3
Out 1
58
HORIZONTAL
59
VERTICAL
UNPOLARISED

FIG 5

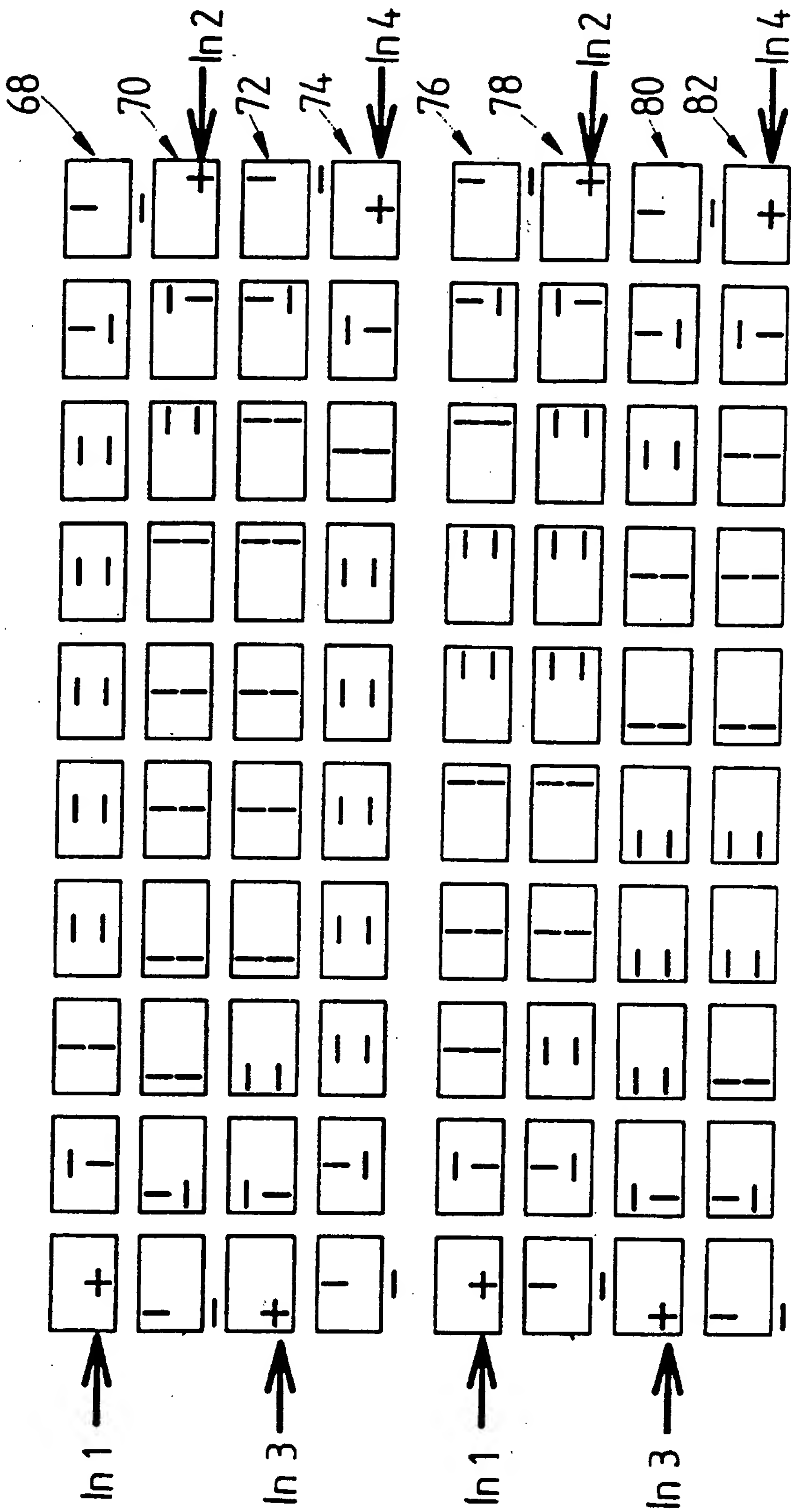



FIG 6

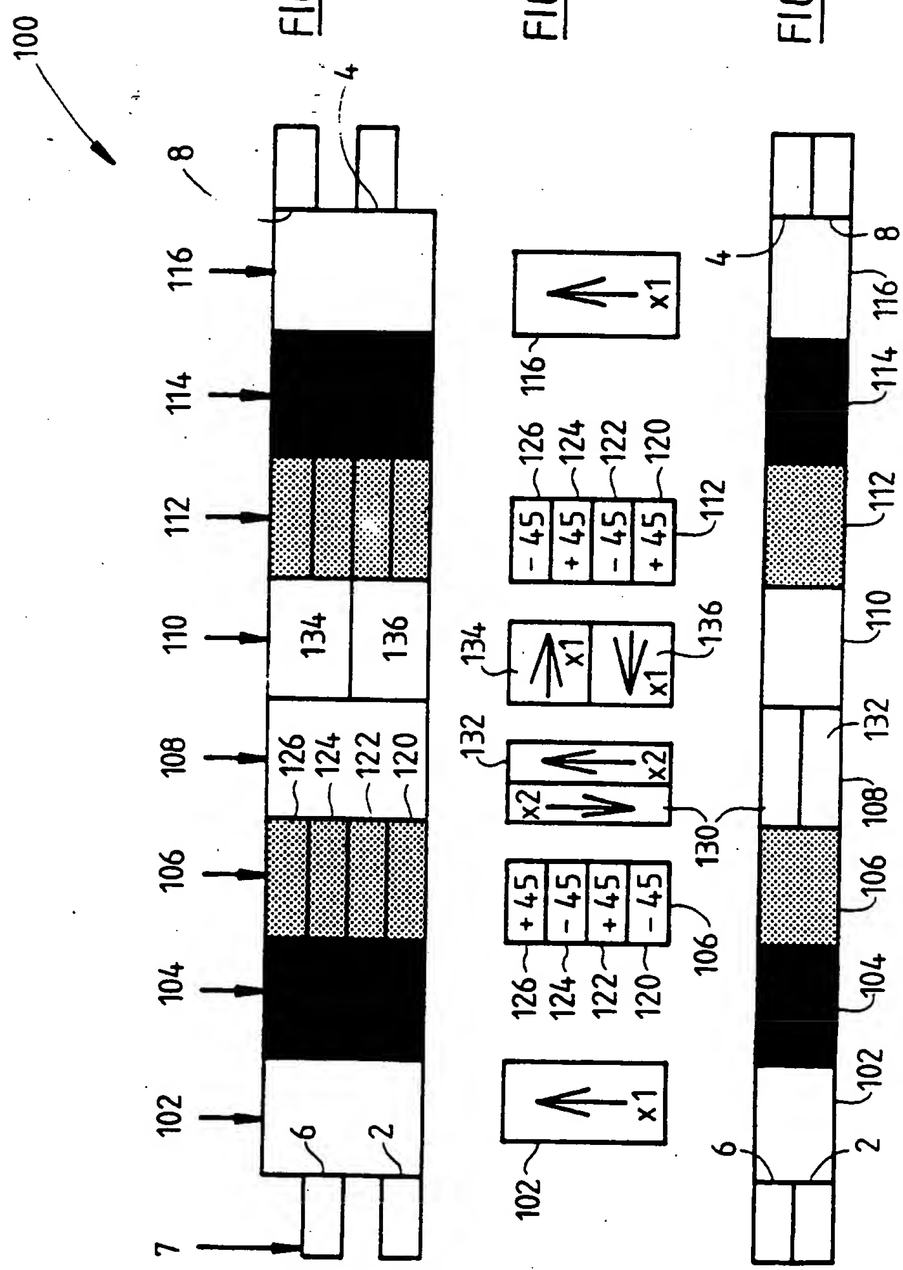



FIG 7

FIG 8

FIG 9

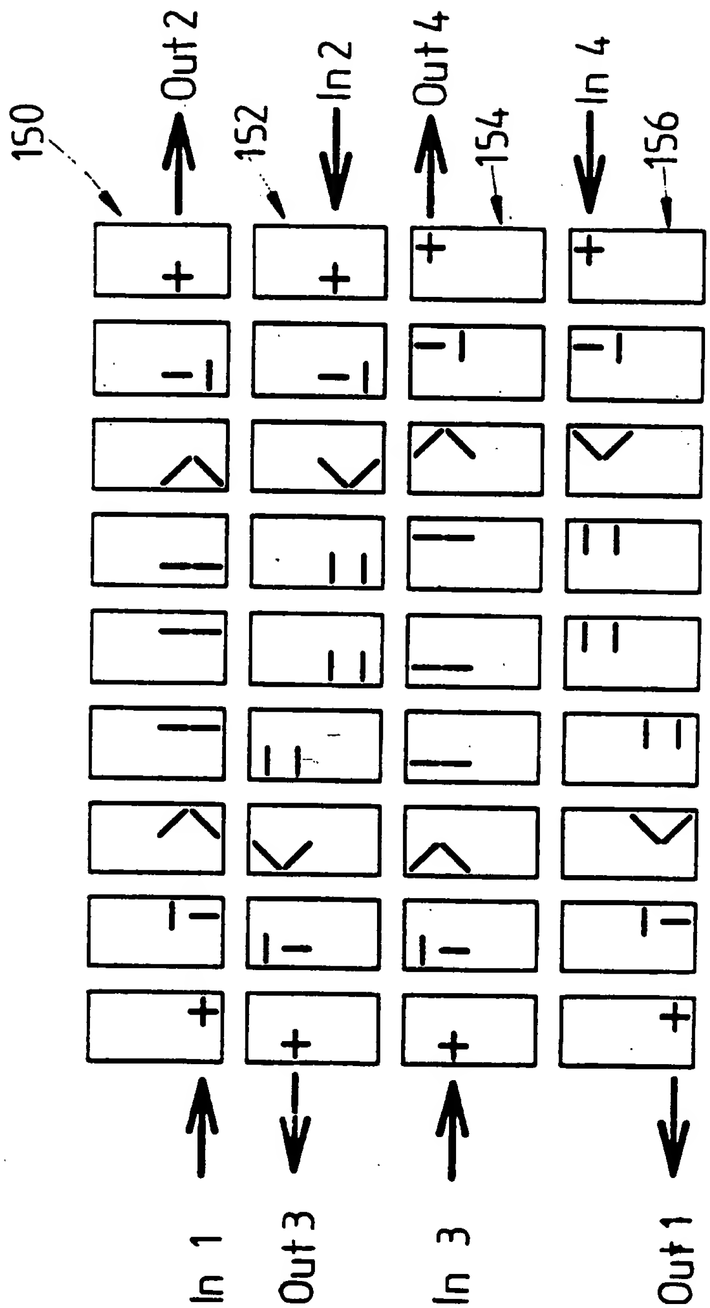



FIG 10

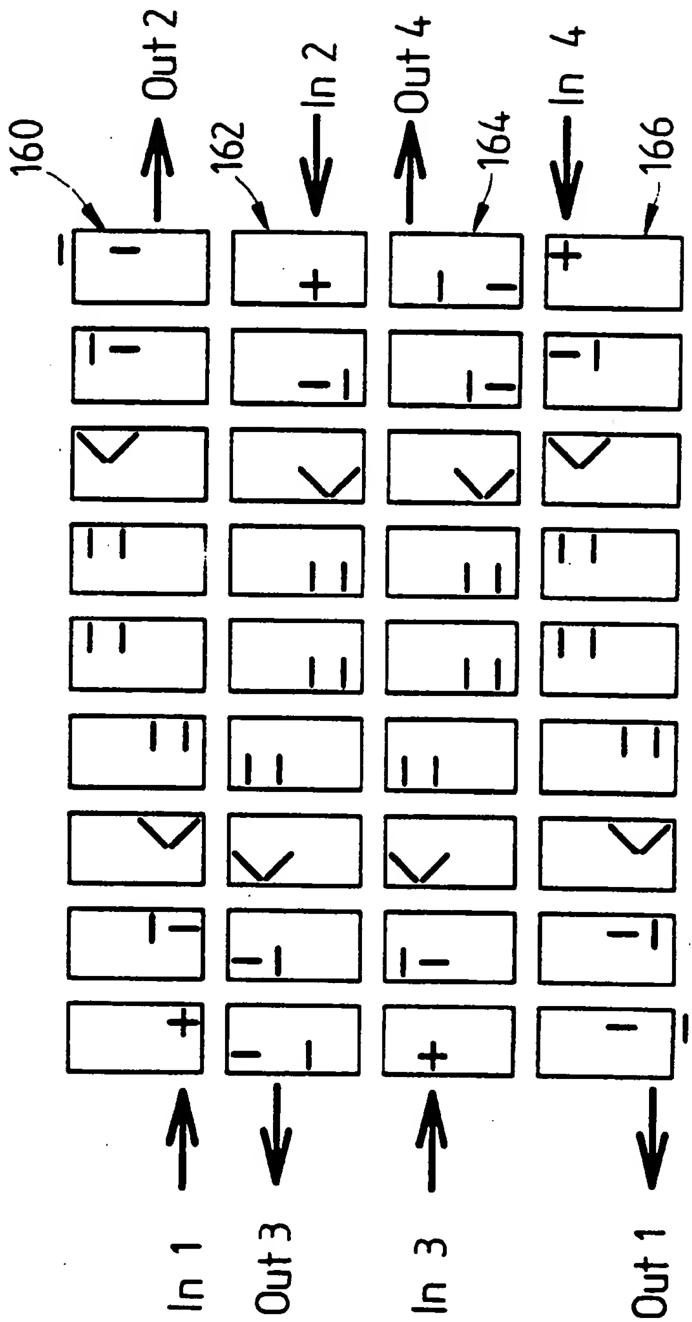



FIG 11

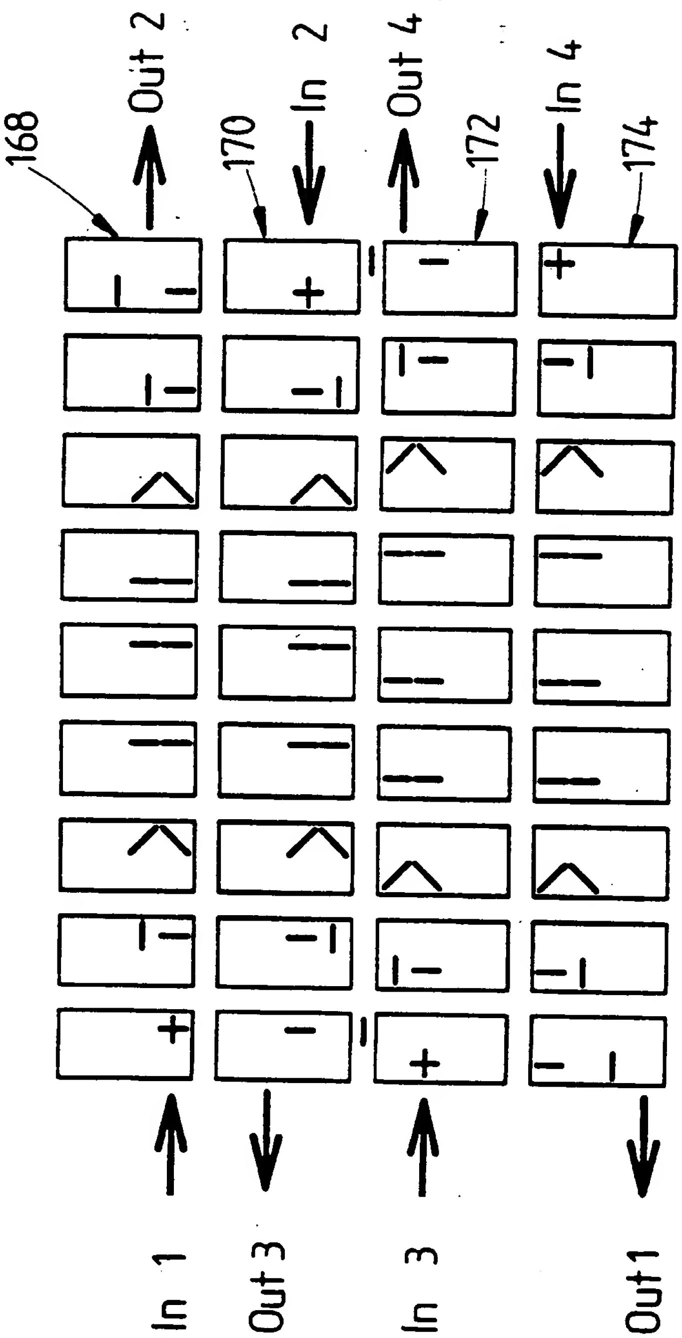



FIG 12

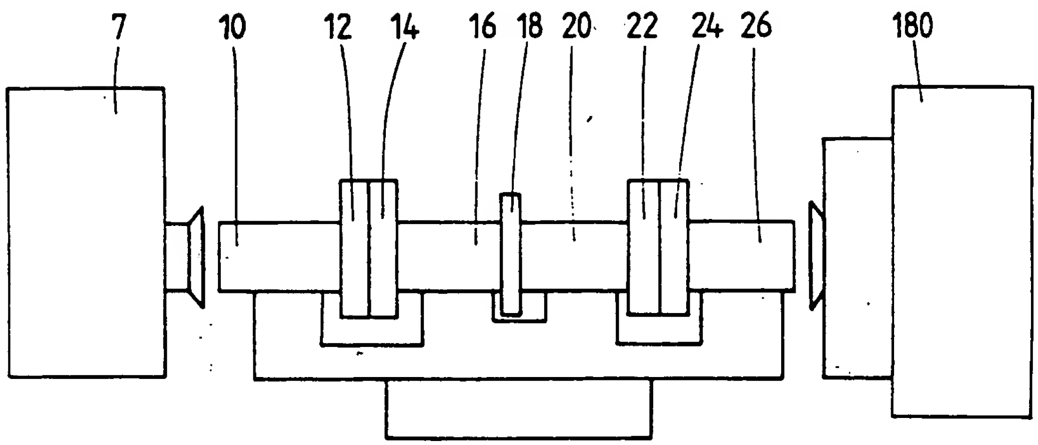



FIG 13

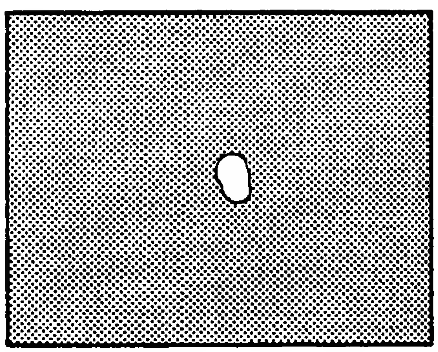


FIG 14

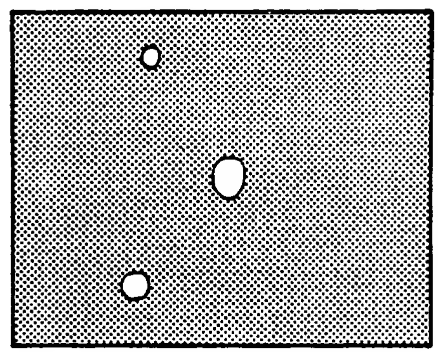


FIG 15

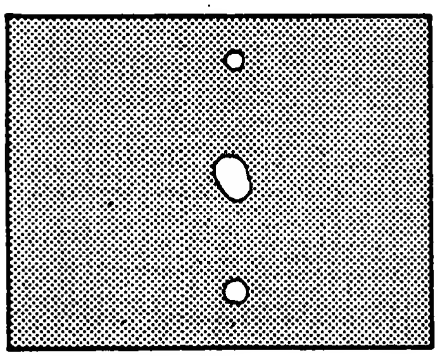


FIG 16

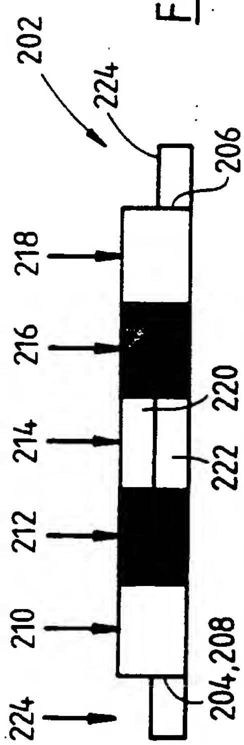



FIG 17

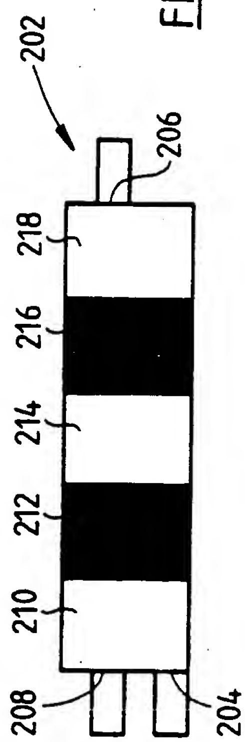



FIG 18

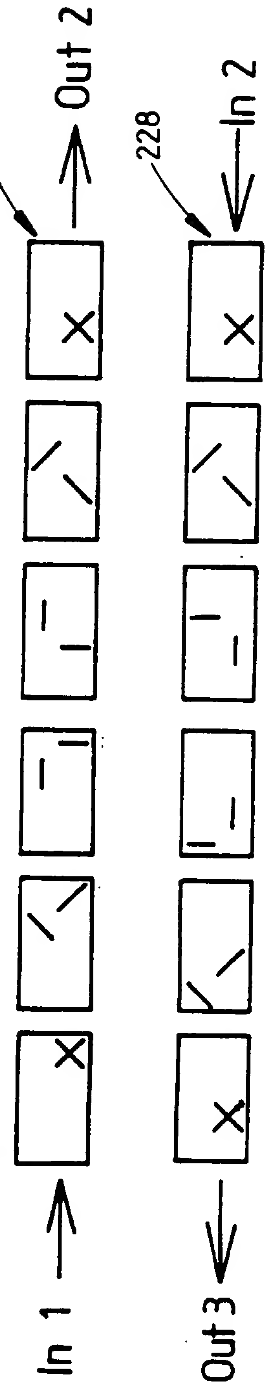



FIG 19

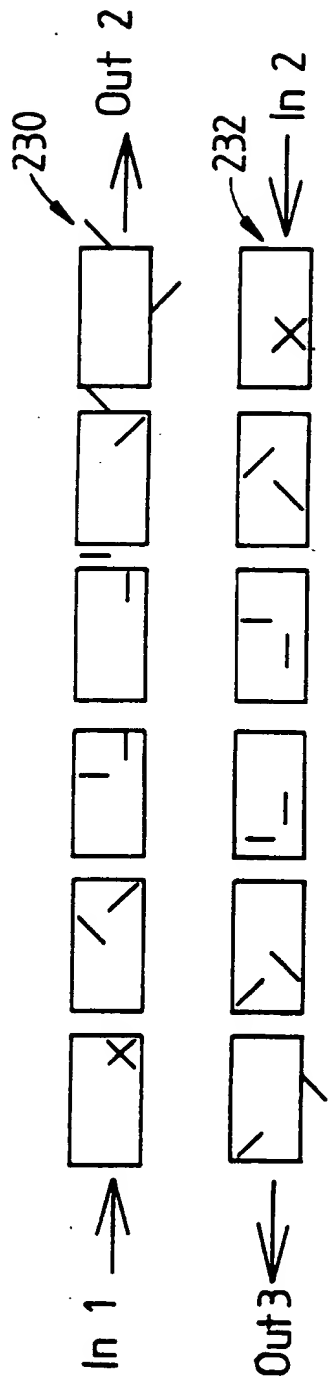



FIG 20

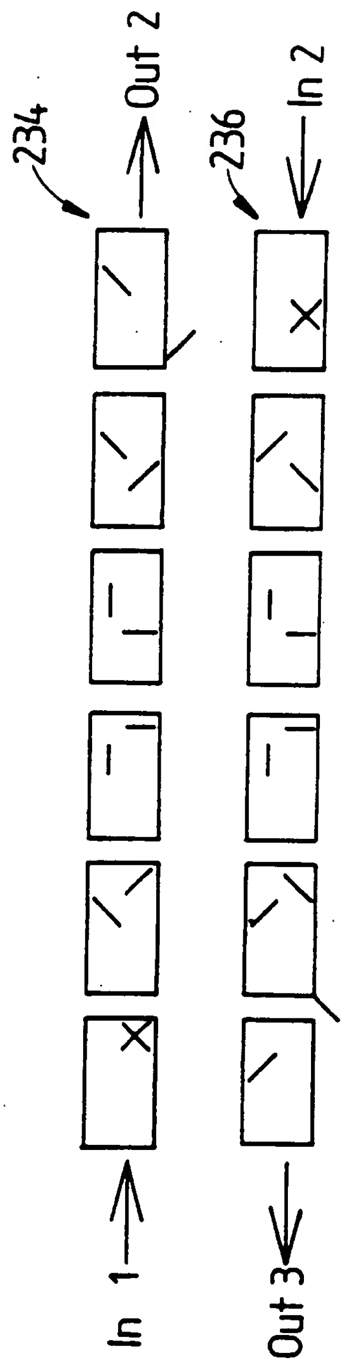



FIG 21

FIG 22

FIG 23

FIG 24

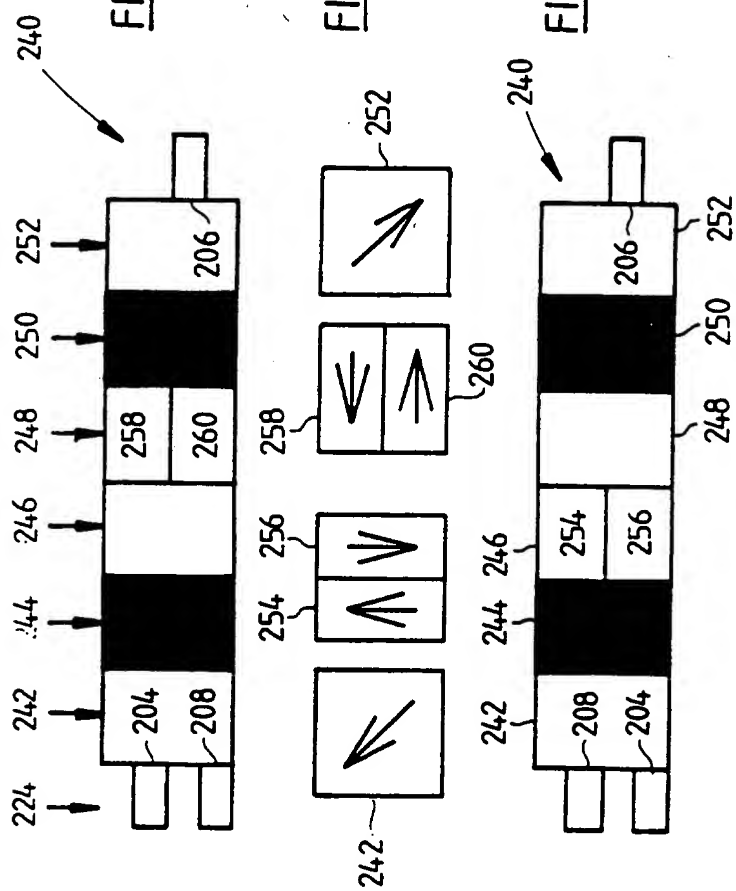
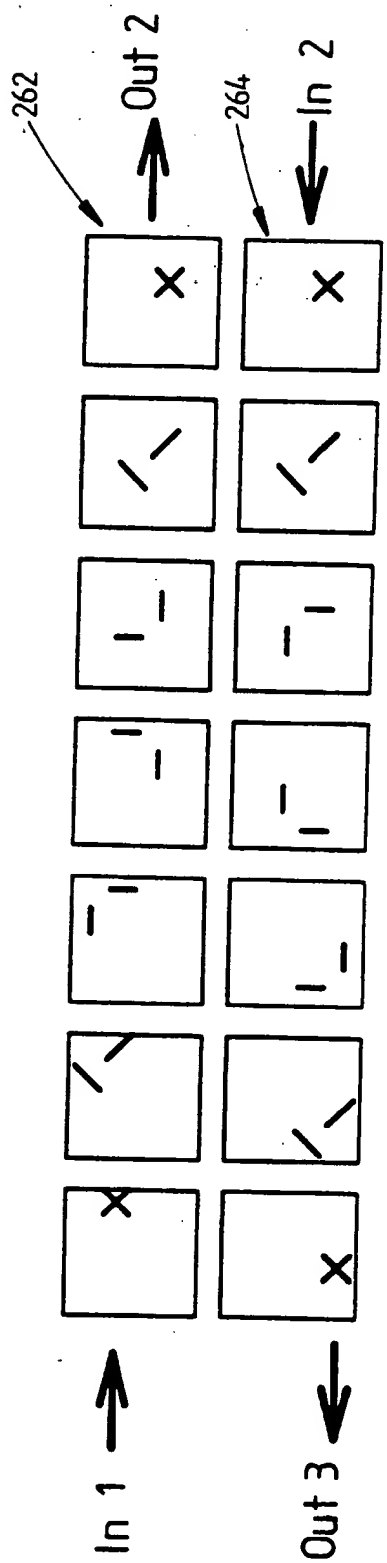


FIG 25



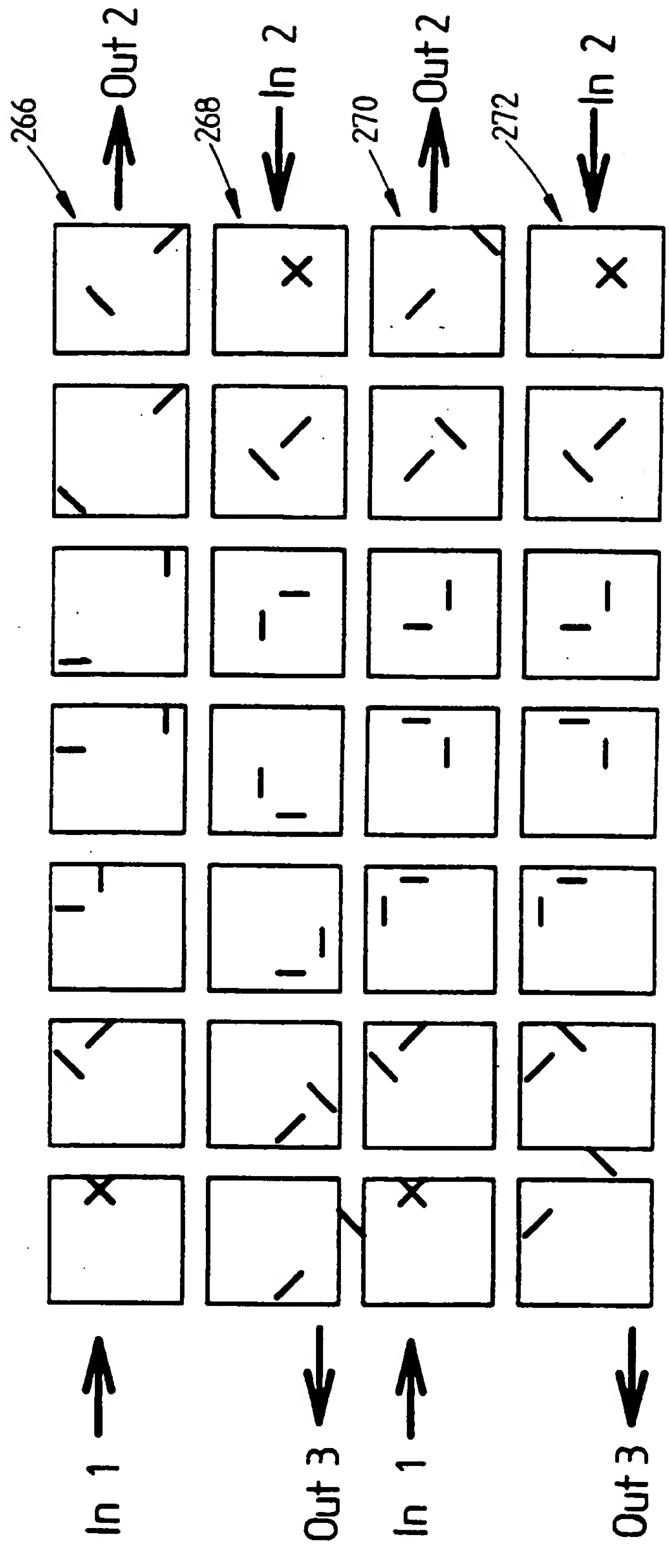



FIG 26

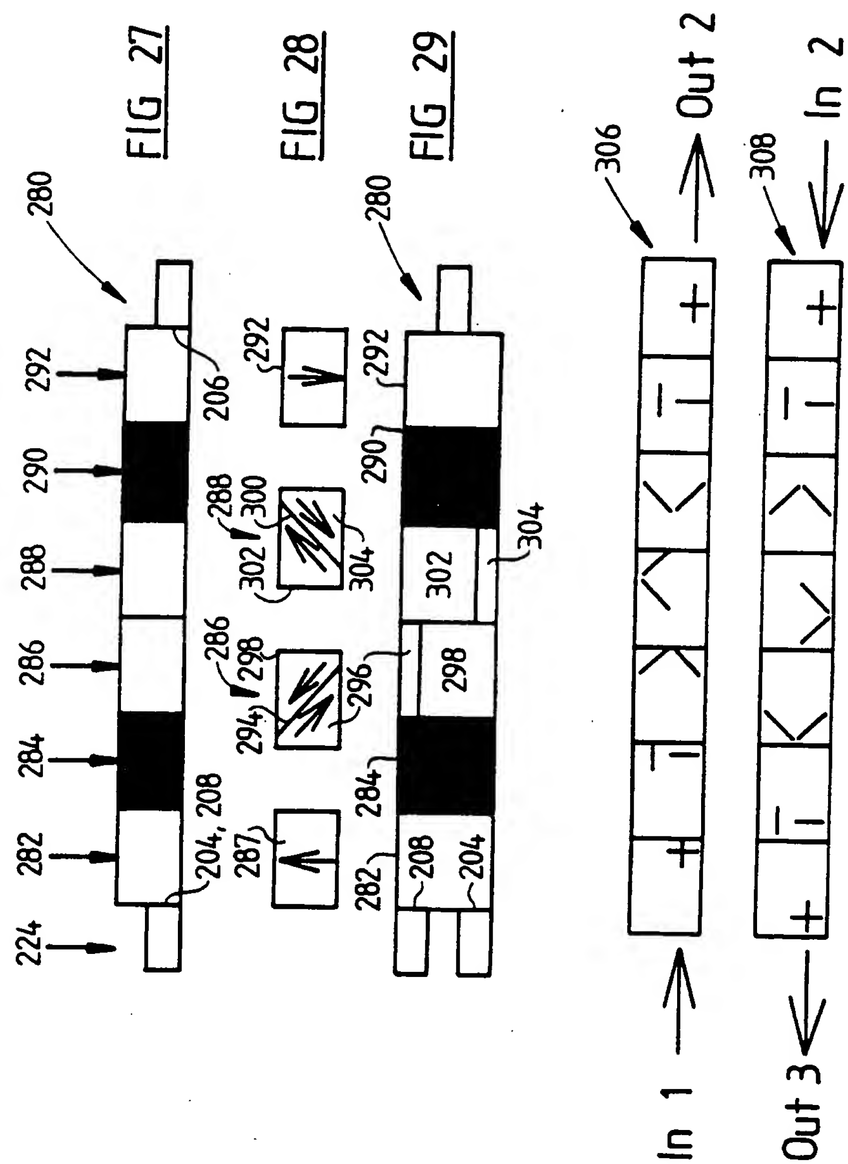



FIG 27

FIG 28

FIG 29

FIG 30

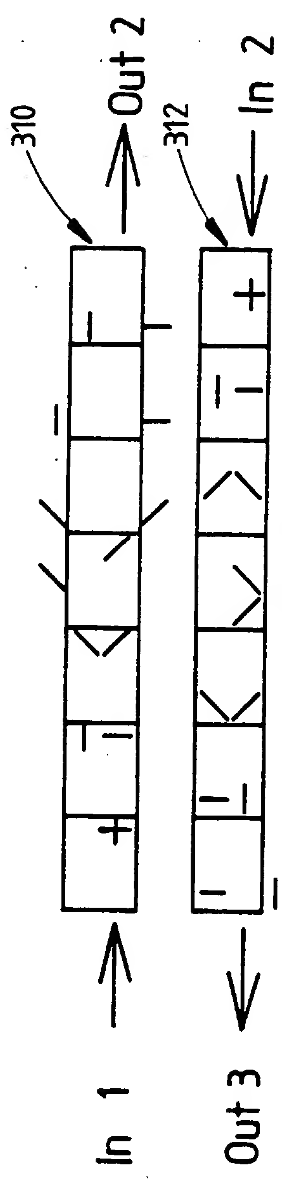



FIG 31

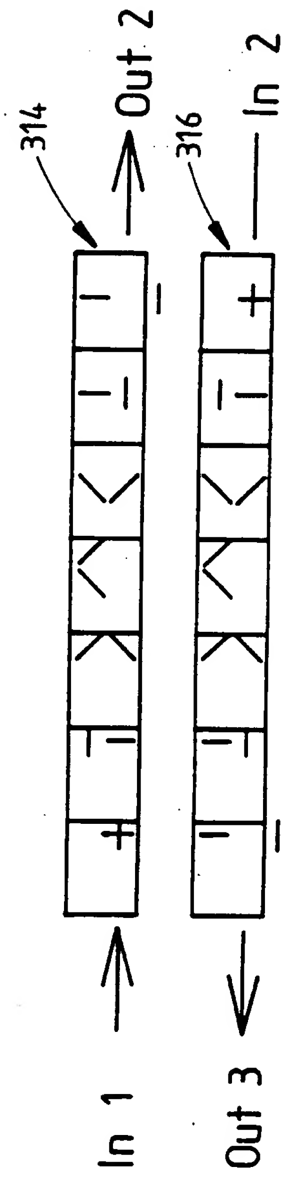



FIG 32

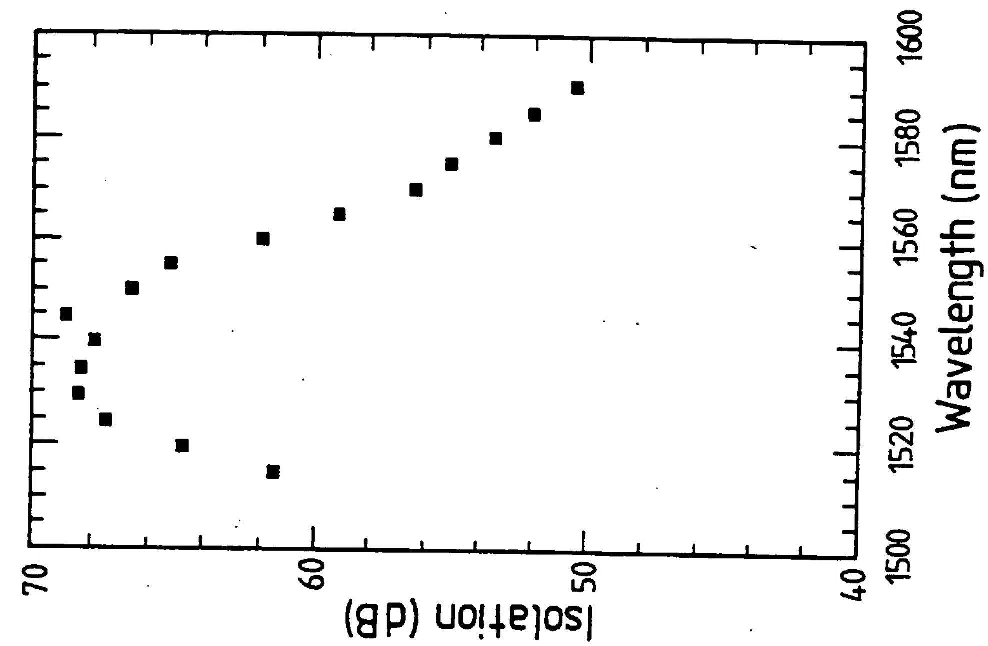

Isolation (dB)
70
60
50
40
Wavelength (nm)
1500
1520
1540
1560
1580
1600

FIG 34

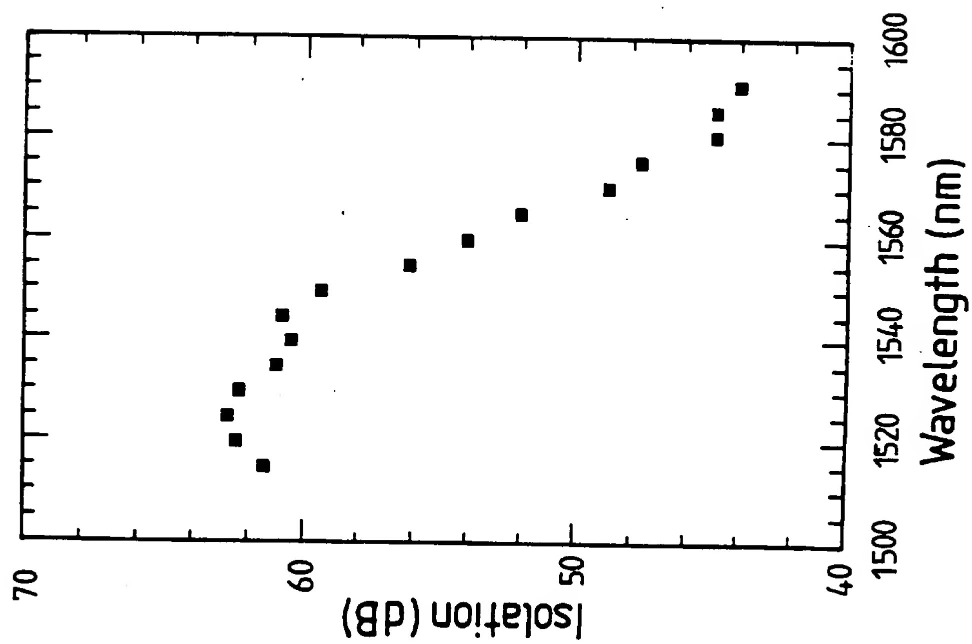

Isolation (dB)
70
60
50
40
Wavelength (nm)
1500
1520
1540
1560
1580
1600

FIG 33

**A. CLASSIFICATION OF SUBJECT MATTER**

Int. Cl.$^5$ G02F 1/09 1/095

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC G02F 1/09, 1/095

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU : IPC as above

Electronic data base consulted during the international search (name of data base, and where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to Claim No. |
|---|---|---|
| X,P | US,A, 5212586 (VAN DELDEN) 18 may 1993 (18.05.93). See whole document. | 17 |
| X,P | US,A, 5204771 (KOGA) 20 April 1993 (20.04.93). See whole document. | 1,17 |
| X | US,A, 4978189 (BLONDER) 18 December 1990 (18.12.90). See whole document. | 1,17 |
| X | US,A, 4650289 (KUWAHARA) 17 March 1987 (17.03.87). See whole document. | 1,17 |

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 18 January 1994 (18.01.94) | 1 FEB 1994 (1.02.94) |

| Name and mailing address of the ISA/AU | Authorized officer |
|---|---|
| AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION<br>PO BOX 200<br>WODEN ACT 2606<br>AUSTRALIA<br>Facsimile No. 06 2853929 | R. CHAO<br>Telephone No. (06) 2832191 |

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate of the relevant passages | Relevant to Claim No. |
|---|---|---|
| X | US,A, 4464022 (EMKEY) 7 August 1984 (07.08.84). See whole document. | 1,17 |
| X | US,A, 4272159 (MATSUMOTO) 9 June 1981 (09.06.81). See whole document. | 1 |
| X | US,A, 4221460 (HEPNER) 9 September 1980 (09.09.80). See whole document. | 17 |
| X | EP,A, 0500157 (KONINKLIJKE PTT), 26 August 1992 (26.08.92). See whole document. | 17 |

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

| Patent Document Cited in Search Report | | Patent Family Member | | | | | |
|---|---|---|---|---|---|---|---|
| EP | 500157 | CA | 2061210 | | | | |
| US | 4221460 | DE | 2840254 | FR | 2403567 | GB | 2005043 |
| | | JP | 54054054 | | | | |
| US | 4272159 | CA | 1128347 | DE | 2947730 | FR | 2443079 |
| | | GB | 2038022 | IT | 7927653 | IT | 1127644 |
| | | JP | 55073016 | NL | 7908628 | JP | 55088009 |
| | | JP | 55088009 | JP | 55113021 | | |
| US,A, | 4464022 | CA,A, | 1217962 | DE,A, | 3335190 | GB,A, | 8325791 |
| | | GB,A, | 2127579 | JP,A, | 59083126 | | |
| US | 4650289 | CA | 1149499 | EP | 15129 | JP | 5412637 |
| US | 4978189 | EP | 429216 | JP | 3171103 | | |
| EP,A | 500157 | CA,A, | 2061210 | | | | |

END OF ANNEX